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Electrical resistivity of sandy soil with water, leachates and seawater

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Electrical Resistivity of Sandy Soil with Water, Leachates and Seawater

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USE OF THESIS

ABSTRACT

Liners are used in the engineered containment systems such as landfills for controlling the migration of contaminants. Although there are several techniques for detecting the leakages through the liners, use of the electrical resistivity method can assist in timely detection of contaminant migration in cost-effective manner. This method is based on the well-established fact that the electrical resistivity of soils and other geomaterials is much higher than the electrical resistivity of water, leachates or any liquid effluents which may permeate the landfill foundation material. Additionally, the geotechnical properties of a soil exhibit a close relationship with its electrical resistivity values for different conditions.

This thesis presents the results of investigation into the interaction between the various electrical factors pertaining to resistivity tests in Perth sandy soil (specifically AC-input voltage and frequency) and those controlling the soil characteristics, specifically water/fluid content and relative density of the soil, and the types of permeant employed in the tests, namely distilled water, tap water, three leachates and seawater. For a landfill system situated near a salt water body, the effects of seawater and seawater-leachate intrusion have also been scrutinized. For the measurement of electrical resistivity for different soil density and contamination conditions, the experimental apparatus was developed as per Australian standard AS 1289.4.4.1-1997 as a significant part of the thesis work.

The test results indicate that the resistivity of the sandy soil is almost independent of both AC-input voltage and frequency within the ranges used, while the choice of electrode material has an insignificant effect on the outcome of tests using this method. It is observed that the resistivity of sandy soil decreases rapidly with an increase in water/fluid content, but the rate of decrease reduces considerably for water contents over 12% in the case of distilled water and 10% for tap water, irrespective of the relative density. The resistivity is found to decrease almost linearly with an increase in relative density. However, the effect of relative density on the electrical resistivity of the soil is found to be negligible at higher water contents.

In the landfills and similar containment systems, there is a possibility of leakage of leachate across the liners and/or seawater intrusion, depending on the location of the landfills. Hence, the study was conducted to evaluate the effects of contamination on the electrical resistivity of the Perth soil by changing the fluid content with various combinations of tap water, three different leachates and seawater. The study shows that for any mix of leachate and tap water, the resistivity decreases rapidly with increasing fluid content; however, the

rate of decrease reduces significantly for fluid contents over 9%, irrespective of the type of leachate. Almost the same trend is observed for the case of seawater.

Correlations between electrical resistivity, water content, relative density, amount and the composition of permeating fluid, which are applicable to the soil and permeating fluids used in the study, have also been developed and presented.

DEDICATION

I would like to dedicate this thesis to my family and especially to my husband, Shashwat S. Pandey, for his unwavering support and encouragement.

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Lopa Mudra S. Pandey

The declaration page
is not included in this version of the thesis

NOTATION

Basic SI units are given in parentheses.

A	cross-sectional area (m^2)
A_l	amount of leachate in the permeating fluid in percentage by volume (dimensionless)
A_s	amount of seawater in the permeating fluid in percentage by volume (dimensionless)
c_1	constant (ohm-m, Ωm)
C_c	coefficient of curvature (dimensionless)
C_o	variable dependent on the composition of the permeating fluid (dimensionless)
C_s	variable dependent on the composition of the seawater (dimensionless)
C_{sl}	variable dependent on the composition of the seawater-leachate mixture (dimensionless)
C_u	coefficient of uniformity (dimensionless)
d^*	critical pore diameter for porous systems (m)
D	diffusion coefficient for same ionic species in clay (m^2/s)
D_{10}	effective size (mm)
D_r	relative density (dimensionless)
EC_0	bulk soil electrical conductivity (S/m)
EC_w	pore water electrical conductivity (S/m)
EC_s	apparent soil-particle-surface electrical conductivity (S/m)
f	input frequency (Hz)
F_{sat}	structural coefficient at saturated condition (S)
FF	formation factor (dimensionless)
g	gravitational acceleration constant (m/s^2)

G_S	specific gravity of soil solids (dimensionless)
G_{s20}	specific gravity at a standard temperature of 20°C (dimensionless)
i	current flowing through the conductor (A)
I	induced electric current in the medium between outer electrodes (A)
k	hydraulic conductivity (m/s)
k_{sat}	saturated hydraulic conductivity (m/s)
k^*	permeability (m^2)
K	a constant; function of the geometry of the electrode pair (m)
$K4P$	four probe conductivity (S/m)
$K(SE)$	electrical conductivity of saturation (S/m)
$K(1:5)$	electrical conductivity for 1:5 extracts (S/m)
Kx	$K(SE)$ or $K(1:5)$ (S/m)
K_T	function of temperature and G_s (S/m)
L	length (m)
LL	liquid limit (dimensionless)
M_o	mass of dry soil (g)
M_a	mass of the flask filled with distilled water to the etch mark (g)
M_b	mass of the flask filled with water and soil to the etch mark (g)
M_s	mass of soil solids in a volume of soil, V (g)
M_w	mass of water in the soil (g)
n	soil porosity (dimensionless)
n^*	efficient porosity (dimensionless)
ρ	resistivity of the soil specimen (Ωm)
ρ'	electrical resistivity of unsaturated soil (Ωm)
ρ_0	soil resistivity (Ωm)
ρ_w	resistivity of free water (Ωm)
PI	plasticity index (dimensionless)
PL	plastic limit (dimensionless)
r	radius of a cylindrical sample of soil (m)
R	resistance (ohm, Ω)

S_r	degree of saturation (dimensionless)
V	potential difference across the outer conductors/ input voltage (V)
ΔV	electrical potential difference between the two inner electrodes (V)
w	gravimetric water content (dimensionless)
w_k	water content at minimum hydraulic conductivity (dimensionless)
w_{opt}	optimum water content (dimensionless)
w_{pf}	permeating fluid / pore fluid/ fluid content (dimensionless)
γ	total unit weight (kN/m^3)
γ_d	dry unit weight (kN/m^3)
γ_{dry}	dry unit weight (kN/m^3)
$\gamma_{d\,\max}$	maximum dry unit weight (kN/m^3)
$\gamma_{d\,\min}$	minimum dry unit weight (kN/m^3)
γ_{wet}	wet unit weight (kN/m^3)
z	distance between equally spaced electrodes (m)
λ	resistivity correction factor (dimensionless)
a, b, β , c, d , c_2, c_3, e, f_0	various constants (dimensionless)

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CHAPTER 1

INTRODUCTION

1.1 General

Engineered containment systems minimize the impact of effluents on the environment and human health through the use of the liner system. Liners are used extensively for contamination control in waste storage and disposal facilities such as landfills, sump wells, red mud ponds, tailing dams, leachate ponds and fly-ash collection pits. Fig. 1.1 shows a typical geosynthetic clay liner (GCL) used at a landfilling facility.

Fig. 1.1 Geosynthetic liner (Courtesy: Millar road landfill and recycling facility, City of Rockingham, Perth, WA)

Liners may be artificial (geomembranes) or natural, like compacted clays (Daniel, 1984; Harrop-Williams, 1985), silty soils (Holtz, 1985), mine tailings (Jessberger & Beine, 1981) and soil bentonite mixes (Chapuis, 1990). Since Environmental Protection Authority (EPA) promulgated the first federal landfill rules in 1991, most landfills have been lined in an effort to isolate the buried wastes and to prevent pollutants from leaking into the groundwater and subsequently, contaminating drinking water supplies. Liners are designed and constructed to create a barrier between the waste and the environment and in the case of the landfill liners, to drain the leachate to collection and treatment facilities; thereby, preventing the uncontrolled release of leachate into the environment.

The long-term integrity of liner materials is critical (Daniel, 1984). However, as the liners endure aggressive hydraulic, mechanical, thermal and chemical environments, the geosynthetic clay liners' (GCLs) durable performance and their insulating efficiency over their intended design life cannot be guaranteed readily (Rowe *et al.*, 2004). Wrinkles and other defects often develop in the geomembrane (GM), in the short- and long-terms, for various reasons, including diurnal temperature variations and poor quality assurance during placement (Nosko & Touze-Foltz, 2000).

The adverse environmental impact of the contaminants intensifies with the passage of contact time. Moreover, the leachate treatment is extremely expensive. As the cost for decontamination increases with the increment in the affected area, timely detection of contamination becomes imperative. The effective control of leachate migration through landfill liners necessitates vigilant monitoring and expeditious repairing of leaks in the liner system (Harrop-Williams, 1985).

Previously used leak detection methods shown in Table 1.1 such as groundwater monitoring wells, lysimeter, diffusion hoses, capacitance sensors, tracers and electro-chemical sensing cables are cumbersome, expensive and the repair involves considerable destruction of the liner (Wilson *et al.*, 1995; Okoye *et al.*, 1995; Kaya & Fang, 1997).

Contamination detection can be achieved in an expeditious, non-invasive manner and at low costs by the proper utilization of geophysical techniques (Sirieix *et al.*, 2013). These methods utilize the changes in electrical properties of the geomaterials observed due to their interaction with contaminants (Abu-Hassanein *et al.*, 1996; Shukla & Yin, 2006).

Table 1.1 Leak detection methods for liners (National network for environmental management studies (NNEMS) report, 1998)

Leak detection method	Advantage	Disadvantage
Groundwater monitoring wells	detects contaminant plumes	doesn't prevent groundwater contamination, expensive, can only detect plumes that pass by the line of wells
Lysimeter	detects contamination	requires laboratory testing, high operating cost, cannot pinpoint the location of the leak
Diffusion hoses	widely available components, automatic, low operational cost	ineffective if leachate does not produce vapor
Capacitance sensors	readily available, automatic	measures all moisture, not specifically leachates
Tracers	can be used at any stage of landfilling, leachate composition not required	operational cost high due to manual collection and testing, does not locate exact leak point
Electro-chemical sensing cables	widely available	detects very narrow range of contaminants, site specific, must be installed during construction phase
Two electrode method	especially useful for detecting leaks in pre-existing landfills	indicates only the existence of a leak, cannot be used for active landfills
Electrode grid method	locates leaks in active and closed solid waste landfills, monitors the entire area below the liner, can detect holes in the liner during construction phase	not applicable to existing landfills, high capital cost for installation stage

The effluents have significantly lower resistivity than the landfill foundation materials. Even a small amount of contaminant permeating the sand and other landfill base geomaterials produces a significant decrease in their resistivity value (Darayan *et al.*, 1998; Yoon & Park,

2001). This change in resistivity can be detected quite easily to locate liner leakages. Fig. 1.2 shows a typical leachate collection pond where the pumped out leachate from landfill is stored. A liner placed over sand or geomaterial base is used for the prevention of fouling. Any trace of contaminant in the under-bed can be attributed to leaks in the liner. Use of the electrical properties of the landfill foundation materials and the leachate will assist in the effective control of leachate migration and will minimize the environmental impact.

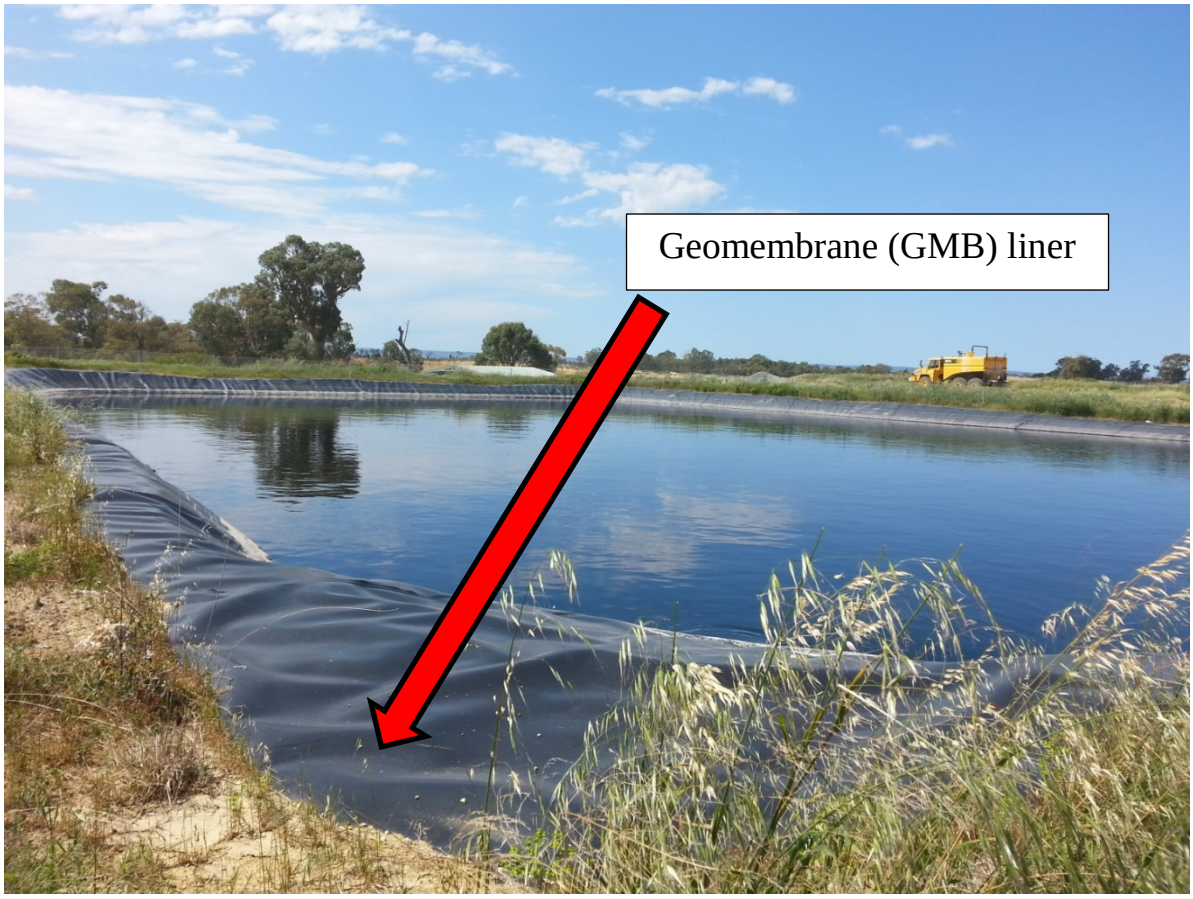

Fig. 1.2 Leachate collection pond (Courtesy: Millar road landfill and recycling facility, City of Rockingham)

As the electrical resistivity of geomaterials is closely related to their geochemical and geotechnical properties (Archie, 1942; Fukue *et al.*, 1999; Gupta & Hanks, 1972; Kalinski & Kelly, 1993; Kibria & Hossain, 2014; Kuranchie *et al.*, 2014; McCarter, 1984; McCarter & Desmazes, 1997; Munoz-Castelblanco *et al.*, 2012; Sreedeep *et al.*, 2004; Yan *et al.*, 2012; Yoon

& Park, 2001), the knowledge of one facilitates primary prediction for the other. Apart from its usage in liner leakage detection, the knowledge of the relationships between the electrical resistivity and geotechnical properties has other useful applications such as for corrosion studies (BSI, 1990a), anomaly detection (Panthulu *et al.*, 2001), soil salinity studies (Adam *et al.*, 2012; Gupta & Hanks, 1972; Rhoades *et al.*, 1977), agricultural applications (Samouelian *et al.*, 2005), etc.

In this chapter, a brief introduction to the electrical resistivity method is presented along with the objectives, the scope and the organisation of this study.

1.2 Electrical resistivity method

The electrical resistivity method works on the principal that the measured voltage drop across a pair of electrodes at a certain current is proportional to the electrical resistivity of the soil. All materials, including soil and rock, have the intrinsic property of resistivity, which governs the relationship between the current density and the gradient of the electrical potential.

The electrical resistivity of the soil is determined by measuring the resistance of the soil. This is done by measuring the voltage across a pair of electrodes at a known current level. However, the measured resistance is not a unique material property. The resistance is proportional to the length and the inverse of the cross-sectional area, of the electrically conducting material being measured. The theory of soil electrical resistivity is based on the Ohm's law given as follows:

$$V = iR \tag{1.1}$$

where

V = potential difference across the conductor (V)

i = current flowing through the conductor (A)

R = resistance of the conductor (Ω).

Resistivity (ρ, Ωm) can be defined by the following equation.

$$R = \frac{\rho L}{A} \tag{1.2}$$

where A is the cross-sectional area (m^2) and L is the length (m).

For the case of a pair of electrodes in a homogeneous, isotropic conducting media there is a linear relationship between resistance and resistivity as given below by the following equation:

$$\rho = KR \tag{1.3}$$

Here K is a constant, being a function of the geometry of the electrode pair.

There are many different kinds of electrical resistivity measurement systems, depending on the current and the electrode array system. A four-electrode array, where measurements are only made with the inner electrodes, minimises the effect of polarization, since the current drawn through the measurement electrodes is very small, so there is no appreciable build-up of ions at the electrodes (Campanella & Davies, 1997). Other studies have also stressed the advantages of four- electrode method over the two-electrode method and AC-input current over DC (Abu-Hassanein, 1994; Yan *et al.*, 2012).

Methods for performing laboratory measurements of soil resistance or resistivity include the use of the Miller soil box (Fowles, 1980) and the use of circular four-probe resistivity cells (Gupta & Hanks, 1972; Rhoades *et al.*, 1976; Rhoades *et al.*, 1977; Kalinski & Kelly, 1993). Different researchers have altered and modified the basic set up to cater to specific needs. Sreedeep *et al.* (2004) fabricated and tested a new electrical resistivity box, which was a highly modified form of the soil box used by Fowles (1980). Munoz- Castelblanco *et al.* (2012) developed a new electrical resistivity probe for the study of influence of change of water content on electrical resistivity of loess samples subjected to controlled wetting and drying.

In this research, tests will be carried out in accordance with AS 1289.4.4.1-1997: determination of the electrical resistivity of a soil - method for sands and granular materials. This method has been detailed in Chapter 3: materials and methods.

1.3 Objectives and scope of the present work

The safe storage and disposal of wastes are challenging problems faced by the global community in the present scenario. As per the World Bank, the world currently generates approximately 1.3 billion tonnes of solid waste per year. Between 2002 and 2025, the global volume of generated solid is expected to increase from 0.68 billion tonnes to 2.2 billion tonnes, meaning the volume will more than triple in just over twenty years. In financial terms, solid waste management costs will increase from today's annual US$205.4 billion to about US$375.5 billion in 2025 (Hoornweg & Bhada-Tata, 2012).

Waste generation has increased in Australia, especially in the past decade, with increase in both landfill disposal and recovery. The amount of solid waste generated increased by 11.4 million tonnes or (35%) from 32,379,000 tonnes in 2002-03 to 43,777,000 tonnes in 2006-07. In 2006-07, of the total waste generated, 48% was disposed to landfill (Australian Bureau of Statistics, 2009-10). As per the National Waste Report (2010) issued by the Department of the Environment, the recycling and waste sector in Australia is valued at between A$7 and A$11.5 billion. If waste generation grows at 4.5% per annum, Australia will generate 81,072,593 tonnes of waste in 2020-21.

The quantification of waste generated in Western Australia (WA) has suffered from a lack of proper reporting system for waste generation and insufficient data currently exists on the nature and quantity of controlled waste produced in the state (Australian Government DEWHA, 2009). However, it can be estimated that the total waste generation in WA in 2008/2009 was more than 6,584,587 tonnes of which 4,752,431 tonnes were stored in the landfill and the rest going for diversion or recycling. In WA, landfill is the most common method of waste disposal (Schollum, 2010). The wastes are made up of commercial and industrial wastes, construction and demolition waste and municipal waste (Goldsworthy, 2010).

As per Stephenson & Hepburn (1955), the soil in Perth and its surrounding regions comprise mainly of sand. The electrical resistivity of sandy soils depends largely on amount and continuity of pore fluid (Yoon & Park, 2001).

Table 1.2 lists the typical resistivity values for sand and sand-clay mixes at different water contents as per AS/NZS 1768-2007. It can be seen from the tabulation that the standard does not give a resistivity value corresponding to dry sand. This is because dry sand has extremely high resistivity. Clean silica is known to act as an insulator.

Similar results were obtained by other studies. Fukue *et al.* (1999) obtained about 10^5 Ohm-m electrical resistivity for dry sands. Another study reported electrical resistivity values from 10^{10} to 10^{14} Ohm-m for silicates (Munoz-Castelblanco *et al.*, 2012).

Table 1.2 Variations in soil resistivity with water content (Source: AS/NZS 1768-2007 Lightning protection standards)

Gravimetric water content (%)	**Typical Resistivity (Ohm-m)**	
	Clay mixed with sand	**Silica based sand**
0	10,000,000	-
2.5	1,500	3,000,000
5	430	50,000
10	185	2,100
15	105	630
20	63	290
30	42	-

Additionally, the electrical resistivity for dry sand or sand-clay mixtures shows a significant decrease with increase in water content. Even for a slight increment in water content from 2.5 to 5%, the electrical resistivity of sand decreases by a factor of 60.

Previous studies have established that contaminants influence the bulk resistivity of soil, because they change the electrical properties of groundwater and soil (Abu-Hassanein *et al.*, 1996). As leachate is electrically very conductive, it is a suitable target for electrical methods (Oh *et al.*, 2008). Consequently, the use of electrical resistivity method for leak location and contaminant detection is significantly viable.

The present study aims to characterise liners by the use of electrical resistivity method. The objectives of this study are as follows:

- Determining Perth sand characteristics
- Investigation into the interaction between the various electrical factors pertaining to resistivity tests in Perth sandy soil, specifically AC-input voltage, and frequency; and those controlling the soil characteristics, specifically water content and relative density of the soil, and the type of water employed in the tests, whether distilled or tap water
- Study of the effect of various leachates on electrical resistivity of the Perth sandy soil
- Scrutinising the changes in electrical resistivity produced by seawater infiltration on landfills located near oceanic bodies
- Development of new correlations for electrical resistivity.

1.4 Publications based on the present work

A research paper based on the experimental and analytical work has been accepted for publication in the "Geotechnique Letters" which is an eminent peer reviewed international journal of Geotechnical Engineering. Two more papers based on the research are under preparation and will be submitted by 31st October 2015. The details of the papers are as follows:

- Pandey, L. M. S., Shukla, S. K. & Habibi, D. (2015). Electrical resistivity of sandy soil. *Geotechnique Letters*, Vol. 5, No. 3, 178–185.
- Pandey, L. M. S., Shukla, S. K. & Habibi, D. (2015). Electrical resistivity of landfill base soil contaminated with leachate. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* (under preparation).
- Pandey, L. M. S., Shukla, S. K. & Habibi, D. (2015). Effects of seawater intrusion and leachate contamination on electrical resistivity characteristics of landfill foundation soil, *Environmental Technology* (under preparation).

1.5 Organisation of the present work

This chapter introduces the research area with a background of the basic concepts involved and an outline of the electrical resistivity method. Information is given about the objectives and scope of the research. Chapter 2 provides an in-depth critical review of previous studies relevant to this research. The materials and methods used have been detailed in Chapter 3. Chapter 4 details the electrical resistivity studies for Perth soil using distilled water and tap water as the permeating fluids. The results of the investigation of the effect of leachates on electrical resistivity have been outlined in Chapter 5. Chapter 6 evaluates the impact of seawater and seawater-leachate infiltration on the electrical resistivity of sandy soil. Various empirical correlations have been developed and presented in Chapter 4, 5 and 6. Chapter 7 concludes the thesis by summarizing all observations and findings.

CHAPTER 2

LITERATURE REVIEW

2.1 General

There are a number of quality publications for the research in the area of interrelation between electrical and geotechnical properties of soils (Gupta & Hanks, 1972; Kalinski & Kelly, 1993; Yoon & Park, 2001; Munoz-Castelblanco *et al.*, 2012). Most of these works focus on the effect of water content, unit weight and pore fluid on electrical resistivity. Although some correlations have been developed in the past for electrical resistivity and water content (Kalinski & Kelly, 1993; Gupta & Hanks, 1972; Archie, 1942; Fukue *et al.*, 1999; Munoz-Castelblanco *et al.*, 2012), the relationships of resistivity with density, input voltages and frequencies, electrode material and permeating fluid type are relatively unexplored. This chapter presents an extensive literature review pertinent to the area of research.

2.2 Electrical resistivity studies

The studies applicable to this research have been divided into subcategories based on the type of media used, for the ease of association.

2.2.1 Sands

Archie (1942), Fukue *et al.* (1999), Gupta & Hanks (1972), Kalinski & Kelly (1993), Yoon & Park (2001), Munoz-Castelblanco *et al.* (2012), Sreedeep *et al.* (2004) are some of the noteworthy researchers who investigated the effect of water content, unit weight and pore fluid on electrical resistivity of soils. Archie (1942), Fukue *et al.* (1999) and Kalinski & Kelly (1993) developed equations for the correlation between soil water content and electrical resistivity.

Archie (1942) suggested the following empirical equations based on lab measurements:

$$\frac{\rho_0}{\rho_w} = (n)^{-c} \tag{2.1}$$

for saturated soils and

$$\frac{\rho'}{\rho_0} = (S_r)^{-d} \tag{2.2}$$

for unsaturated soils, where,

S_r = degree of saturation

ρ' = electrical resistivity of unsaturated soil

ρ_0 = soil resistivity

ρ_w = resistivity of free water

n = soil porosity

c and d = soil parameters.

Fukue *et al.* (1999) proposed that the electrical resistivity for a cylindrical sample of soil with electrical resistivity (ρ_0) and radius (r') can be calculated using the following equation:

$$\rho(\frac{\rho_0}{\rho_w}) = \frac{\pi r'}{n(1-F_{sat})} \tag{2.3}$$

where F_{sat} is the structural coefficient at saturated condition and the rest of the parameters are as defined above.

Gupta & Hanks (1972) investigated the effect of water content on the electrical conductivity of soil. The relationship between four-probe conductivity and soil salinity for two soil samples at different water contents was studied. Acrylic cups with internal diameter 101 mm and 50 mm height were fixed with eight equally spaced stainless steel bolts of 0.048 mm outer diameter. This was done to enable eight replicate readings with each soil specimen. By using a solution of known electrical conductivity, the cell constant K_c was determined to correct geometrical errors. Soil samples were prepared with different water and salt (potassium chloride,

KCl) content and their bulk densities were measured. Four probe conductivity ($K4P$), electrical conductivity of saturation ($K(SE)$) and electrical conductivity for 1:5 ($K(1:5)$) extracts was noted. The data was tabulated and mathematically analysed. Bulk density was found to have insignificant effect on the results. The following relation was also proposed based on the study.

$$\frac{K4P}{Kx} = aW + b \tag{2.4}$$

Here Kx is $K(SE)$ or $K(1:5)$ and a, b are constants from regression analysis. It was found that for each soil type, the calibration of four-probe conductivity with saturation extract is necessary. The method was found to be useful for swift soil salinity determination provided water content could be determined independently.

Kalinski & Kelly (1993) developed a relation between soil electrical resistivity and hydraulic parameters. The resistivity of fine grained soil samples were measured using a sequence of circular four-probe resistivity cells. The specimens were soaked in water and adjusted with sodium chloride or potassium chloride. The volumetric water content (θ) was adjusted using pressure membrane apparatus. For each value of θ, the average of the 8 resistance readings were recorded and the specimen was weighed. After all testing, gravimetric water content (W) and dry density was computed. From the results bulk soil electrical conductivity EC_o was defined in terms of pore water electrical conductivity EC_w and apparent soil-particle-surface electrical conductivity EC_s as given by equation (2.2). The result is exclusive to this study.

$$EC_o = EC_s + EC_w\theta(1.04\theta - 0.09) \tag{2.5}$$

The research concluded that laboratory established relationships between electrical resistivity and θ can be used to for the estimation of in-situ volumetric water content, when the pore- water conductivity can be established.

Kuranchie *et al.* (2014) studied the effect of relative density of sand, electrode depth and electrode spacing on the electrical resistivity for dry Perth sand. The resistivity was measured

using the Wenner array experimental set up for different relative densities (varied from 0 to 100%), electrode depths (varied from 100 to 300 mm) and electrode spacing (varied from 100 to 180 mm). Additionally, a numerical simulation was carried out using the software COSMOL for a specific arrangement with electrode depth of 150 mm and spacing of 180 mm. The electrical resistivity values for dry Perth sand ranged from 60,606 (for very dense condition) to 142,857 Ωm (for very loose condition). The results indicate that while the electrical resistivity is inversely related to electrode depth and relative density, it shows a direct relation to electrode spacing. Electrical resistivity ρ was calculated using the equation (2.3):

$$\rho = 2\pi\lambda(\frac{\Delta V}{I}) \tag{2.6}$$

where

ΔV = electrical potential difference in volts (V) between the two inner electrodes

I = induced electric current in amperes (A) in the medium between outer electrodes

z = distance between equally spaced electrodes and

λ = resistivity correction factor.

A resistivity correction factor, λ of 0.46 was obtained for this particular experimental set up. A significant deduction from this study was that λ was found to be independent of the type of soil used.

2.2.2 Clays

McCarter (1984) illustrates the relationship of electrical resistivity of clay with water content and degree of saturation. Electrical resistivity was measured for Cheshire clay (liquid limit, LL =25%; plastic limit, PL =15%) and London clay (liquid limit, LL =65%; plastic limit, PL =28%) using two-electrode method. Test results for the two clays were obtained with constant water content while altering the degree of saturation. Graphs of resistivity versus fractional volume of water were found to be similar for the two types of clay. It was noted that the trends

for these graphs resembled the trend of water content-resistivity observed in previous studies. It was seen that decreasing the degree of saturation resulted in an increase in electrical resistivity of the clay samples. The gradient of resistivity versus degree of saturation curve reduces with a rise in the water content. At water content around plastic limit, resistivity remains almost constant with increase in degree of saturation.

Kibria & Hossain (2012) studied the trend of electrical resistivity with changes in water content, unit weight, degree of saturation, specific surface area (SSA), pore space and ion composition for soil samples. Six soil samples classified as highly plastic clay (CH) were chosen for the study of the relationship of resistivity with geotechnical parameters. High energy X-ray fluorescence tests and scanning electron microscopy (SEM) were used to determine the clay structure, pore distribution and composition of soil samples. Electrical resistivity measurements were made using Super Sting IP resistivity equipment. Montmorillonite was identified as the dominant clay mineral for the soil samples. Resistivity decreased with increase in water content. However, it became nearly constant after 40% water content. Soil resistivity showed a downward trend with increase in unit weight but the effect became negligible for water content greater than 30% as well as for unit weight more than 15.72 kN/m^3. A significant result of the study is that soil resistivity is less sensitive to unit weight than to the water content. The degree of saturation was found to be inversely related to the resistivity. Soil resistivity was directly proportional to SSA and percentage of Calcium ions but the effect was found to decrease with increasing water content. Resistivity became independent of SSA at 30% water content and 14.2 kN/m^3 dry unit weights. Similar observation was made for calcium content at 30% water content. Electrical resistivity of soil registered an increase and then a decrease with increase in pore space. This effect was greater at lower water content (18%).

Giao *et al.* (2003) demonstrated that electrical resistivity measured in field and obtained in the laboratory exhibits similar values. 2D electric imaging technique using SYSCAL R2 resistivity meter was used in four different sites for the mapping of clay deposits. The resistivity data was analysed using RES2DINV. 50 core samples of cylindrical shape with 75 mm diameter and 110 mm length were made and tested in laboratory using four-electrode configuration. Additionally, the electrical resistivity values for Pusan clay were compared to 20 other natural clay samples collected worldwide. The electrical imaging technique was found to map the region very effectively for the upper layers to a depth of 27 m, but the bottom layers of clay could not

be mapped in this study. The electrical resistivity parameter could be useful in mapping clay deposits provided the maximum dipole spacing is three times the depth of the clay bed. Furthermore, for ground improvements the electrical resistivity values showed an increase with time indicating that improved ground strength leads to higher electrical resistivity. However, the study fails to establish a clear correlation between electrical resistivity and other geotechnical parameters (such as water content, plasticity index, unit weight, salinity and organic content) for Pusan clay. It was highlighted that for the laboratory tests, the measured electrical resistivity values were independent of the depth of penetration of the electrodes as well as the specimen geometry. The electrical resistivity data of Pusan clay along with 20 other clay samples was found to vary from 1 to 12 Ωm.

Frempong & Yanful (2005) assessed two tropical clayey soils to determine their suitability for use as landfill liner materials. Two soil samples were obtained from Ghana for the purpose of the study. Leachate from W12 landfill site, London, Ontario was procured. The basic soil properties were established as per ASTM standards. Before the Atterberg limit tests the soil samples were mixed with leachate or water and allowed to stand for 2 days. Fixed- wall permeameter method was used to establish hydraulic conductivity of soils permeated with 0.01N $CaSO_4$ followed by MSW (municipal solid waste) landfill leachate. The pH, organic content, glycol retention value and CEC (cation exchange capacity) were also calculated before and after permeation. Additionally, XRF (X-ray fluorescence) and XRD (X-ray diffraction) techniques were employed to see the effect of permeation on soil mineralogy. The acidity of both soils was found to decrease after permeation as the leachate had an alkaline nature. It was noted that the organic content and CEC showed an increase while the glycol retention values were found to decrease. The hydraulic conductivities for the samples after permeation with the leachate for 6 months were found to be well below acceptable limits ($7.8\text{-}9.0 \times 10^{-11}$). Hence, both soil samples were found to be suitable for use as landfill liner materials. Significantly, the leachate did not affect the strength of the soil specimens adversely.

Van Ree *et al.* (1992) used undisturbed field samples of liners to calculate the permeability values for natural clay and sand-bentonite liners. Rectangular samples (66 mm diameter, 150 mm height) were collected using thin-walled tube samplers or the Begemann continuous sampling system. Permeability measurements were carried out using a modified triaxial cell capable of holding ten samples. After the constant head method, reading were taken after 3, 7 and 10 days

for the period of 12-24 hours to achieve a test cycle of 14 days. Actual permeability of liners determined from undisturbed samples was found to be very sensitive to field conditions. Disturbing the samples caused a decrease in permeability. Placement conditions had a more pronounced effect on sand-bentonite mixtures compared to tertiary clay. The results indicated that 10% bentonite should be used for sand-bentonite liners. Permeability values were independent of original water content and type of cell used. However, degree of saturation was found to cause variation in the permeability values. A decrease in permeability with time was noted which was attributed to hydration and swelling of clays. Geochemical processes were shown to have a significant impact on liners. The study recommends that permeability tests be carried out at complete saturation and without disturbing the sample for optimum results.

2.2.3 Sand-clay mixtures

Kibria & Hossain (2014) studied the variation in electrical resistivity due to different bentonite contents in sand-bentonite mixtures. Sodium and calcium bentonite were mixed with sand at an increment of 20% to fabricate 10 soil samples. The electrical resistivity response was recorded for changes in dry unit weight from 11.8 to 14.9 kN/m^3 and water content from 10 to 40%. Tests to determine particle-size distribution, Atterberg limits, specific gravity and cation exchange capacity (CEC) were conducted along with scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The index properties were found to show a linear increase with decreasing sand content. Test results implied that higher mineral contents caused significant reduction in resistivity. At 40% saturation, for increase in Na-bentonite content from 20% to 100%, resistivity decreased from 14.4 to 8.8 Ωm. For the same saturation and content variation in Ca-bentonite content, resistivity was found to decrease from 29.2 to 10.1 Ωm. Soil samples with Na-bentonite were found to have resistivity ranging from 9.5 to 2.2 Ωm for saturation values ranging from 29.4 to 91.4%. When saturation was varied from 30.1 to 94.8% in Ca-bentonite soil samples, resistivity dropped to 0.9 from 18 Ωm. The study purports that changes in bentonite type and content significantly affect electrical resistivity of soils. However, with an increase in the degree of saturation there is no significant effect of mineral content, CEC and plasticity indices on resistivity.

McCarter & Desmazes (1997) purported the use of electrical properties for soil

demarcation. A cylindrical perspex modified consolidation cell of 66 mm internal diameter and 65 mm height was fitted with top and bottom plates along with six circumferential electrodes. Low frequency (<100 kHz) conductivity measurements were taken for diagonally opposite pairs (E1, E2 and E3) and for the vertical plates (E4). The sample with 71% initial water content was subjected to standard incremental load odometer testing with 48 hours for each load increment. The void ratio and the conductivity were found to decrease with increase in effective stress. Significantly, the trend of both these curves was similar reiterating that electrical conduction in saturated soil takes place through interstitial water. A difference in horizontal and vertical conductivity values pointed to anisotropy in the sample. The ratio of these conductivities indicated the ratio of permeability for both the directions. The study proposed the following relationship between permeability k^*, formation factor FF and critical pore diameter d^* for porous systems.

$$k^* = \frac{\beta d^{*2}}{FF} \tag{2.7}$$

β is a constant for a particular type of clay. The diffusion coefficient, D for same ionic species in clay was also estimated. However, a major drawback is that the data obtained from these relationships can only be used as first approximations. Also, the studies are specific to a certain type of clay and cannot be generalised.

Panthulu *et al.* (2001) used electrical resistivity and self-potential (SP) methods to delineate potential seepage paths in earth dams. Two saddle dams were considered for the study. AC Terrameter, SAS-300 was used. Boreholes were made on predetermined profile lines along these dams and filled with water 5-6 hours before measuring SP data. Reading were taken 2-3 times for SP of each profile using two non-polarizing electrodes, one at a fixed station and the moving along prefixed lines and points. Electrical profiling (EP) was carried out using multi electrode spacing and Schlumberger array method. 1-D interpretation was used to interpret the data. The results indicated weathering for upto 6-m depth, the deeper strata were found to be less weathered. Fractured or weathered isolated pockets along with potential seepage paths and directions could also be located. The results obtained by resistivity methods were corroborated with results observed from geological mapping. Presence of water in piezometers and bore holes

drilled after survey, confirmed the results. SP and EP method was found to be very efficient; however, the study leaves further scope for research to establish this theory.

Mollins *et al.* (1996) established a design model based on the clay void ratio, the sand porosity and tortuosity to estimate the hydraulic conductivity of a sand and sodium bentonite mixture. Na-bentonite powder and compacted sand-sodium bentonite mixtures containing 5, 10 and 20% bentonite by weight were subjected to one-dimensional swelling tests and hydraulic conductivity tests at vertical effective stresses from 1 to 450 kPa. For a particular confining stress, swollen Na-bentonite powder was found to reach a unique void ratio. This void ratio and the logarithm of vertical effective stress exhibit a linear relationship. The study asserted that low bentonite content resulted in higher hydraulic conductivity values compared to the values estimated for a uniform mixture. This observation was attributed to uneven bentonite distribution. A threshold stress value was noted which was a function of clay content. It was discovered that this value characterised swelling behaviour of the mixtures. Above all, the study proposed that if the properties of a particular bentonite are known then the hydraulic conductivity of a sand-bentonite mixture can be predicted from the bentonite content, sand porosity & tortuosity and the vertical effect stress.

Kenney *et al.* (1992) investigated the effect of sand-bentonite ratio, compaction water content and system chemistry on hydraulic conductivity for compacted mixtures of sand and bentonite. Ten test samples of sand-bentonite mixture were made, using either distilled water (or freshwater) or salt water (40 g/l NaCl solution) as the mixing fluid. Permeability tests were carried out using modified conventional consolidometer equipment. Later, the pore fluid was replaced in seven test samples to study the changes in permeability due to the changes in pore-fluid chemistry. The paper suggests that for bentonite-sand mixes with up to 20% bentonite content, sand forms the load supporting framework. The hydrated bentonite occupies the voids and acts as the seepage barrier. It is found that the hydraulic conductivity of bentonite-sand mixture decreases at higher bentonite-sand ratio (B/S) as well as for improved mixing. Higher water content ($1< w_{opt} <1.3$) at the time of mixing and compaction is found to increase bentonite distribution and lower the hydraulic conductivity. Hydraulic conductivity of mixtures with w_{opt} equal to 1 or larger approaches the value of hydraulic conductivity of ideal mixtures when B/S exceeds 10%. As hand mixing in laboratory is more thorough than machine mixing in field, the laboratory-determined values for hydraulic conductivity were the lower limit values. The study

concluded that as the hydraulic conductivity of high swell bentonite mixtures showed minimal increase due to permeation with a strong saline solution, the bentonite fabric was unaffected by this system change.

Alston *et al.* (1997) tested several sand-bentonite liners with different silt supplements and bentonite contents to determine the combination which gave the lowest hydraulic conductivity (10^{-10} m/s). Native sand was used along with bentonite and silt (procured from three alluvial silt sources). Falling-head permeability test using compaction permeameter test apparatus was used to obtain the hydraulic conductivity. Each specimen was arranged in a three layer system with the test specimen (50 mm thick) enclosed between layers of native sand (each 25 mm thick). Standard Proctor hammer was used to compact the layers to achieve 95% maximum dry density at optimum water content (OMC). For one of the test samples, a slice of 2 mm thick High-density polyethylene (HDPE) membrane was vertically set in the middle layer such that it intersected the top and bottom soil layers. Prepared samples were placed under water for 1-2 days for hydration. Then a hydraulic gradient (average value of 60) was applied, permeant fluid was collected and allowed to stand. After 14 days, mill effluent was used as the permeating fluid for all samples except one which was permeated with water for 1 year. Initial testing with tap water showed that one of the silt samples has very low fine sand content and hence resulted in high hydraulic conductivity. The other two samples were then subjected to long-term testing (trial period of 1 year). Based on initial testing, samples were prepared for coarse to fine aggregate ratio of 75:25 and 70:30 mixed with different bentonite contents. In the final test stage, 75:25 and 70:30 samples with 5, 5.5 and 6% bentonite were tested in the same set up but with hydraulic gradient 80 for 84 days. Single-stage borehole test was also carried out for the in-situ measurement of hydraulic conductivity for the constructed liner. In-situ density tests, methylene blue test and grain-size distribution tests were also carried out to evaluate the performance of the liner. As a result of the three stage process, 75:25 (sand to silt aggregate ratio) with 5.5% bentonite was chosen for liner construction. In the second stage, the hydraulic conductivity was found to increase after several months. To amend this, the increase the vertical effective stress was increased by replacing the upper sand layer with steel shot (25 mm thick), which resulted in a significant reduction. Following the observation, the equipment was modified for two samples (one with embedded HDPE) to increase the upper layer thickness (300 mm). Both gave positive outcomes. A significant observation is that the single-stage borehole tests gave repeatable results

with thinner compacted liner. The construction phase borehole test results reconfirmed the efficacy of proposed liner system.

Chapuis (1990) analysed the soil permeability tests for 45 sand-bentonite mixes used as liners in landfills. Due to the different testing methods used, the results had a wide range of values for parameters like bentonite content, degree of saturation, hydration period and amount of swelling. The hydraulic conductivity (k) was found to have a poor correlation to porosity, bentonite content or total fines content individually. The hydraulic conductivity showed a correlation to the efficient porosity (n^*), corresponding to pore space available for seepage of fast moving water. Two methods were proposed to predict the value of k. Based on the prediction, appropriate soil can be chosen and bentonite content can be estimated as per requirement. There are limitations to the methods as the predicted k values are within one order of magnitude of the experimental values obtained for sand-bentonite mixtures with degree of saturation more than 90%. Hence, laboratory permeability tests must be performed to determine hydraulic conductivity with accuracy.

Stewart *et al.* (1999) proposed a model to predict the swelling and hydraulic conductivity of bentonite-enhanced sand (BES) mixtures in water as well as salt solutions using the data presented by Studds *et al.* (1996), Mollins *et al.* (1996) and Studds *et al.* (1998).The specimens with 10% and 20% bentonite content along with data for bentonite alone were analysed. The hydraulic conductivity exhibited a direct relationship with bentonite percentage and bentonite void ratio. Initial water content was found to have a significant impact on volumetric shrinkage of BES and therefore on cracking due to desiccation. Bentonite content also showed a slight impact on shrinkage. The study concludes by putting forth a model to predict engineering behaviour of BES with known tortuosity relationship for the coarse soil used in the mixture.

2.2.4 Compacted clay liners (CCL) and geosynthetic clay liners (GCL)

Abu-Hassanein *et al.* (1996) scrutinised the relationship of electrical resistivity with compaction conditions, index properties and hydraulic conductivity for ten soils. Specimens were taken from ten compacted soil liners with low hydraulic conductivity (below 10^{-9} m/s). X-Ray diffraction was used to determine the mineralogy along with four point sensing method for electrical

resistivity measurement. AC current with electrical potential 35 V and 60 Hz constant frequency, was used. The samples were compacted using standard, modified and reduced Proctor methods. Oven (T = 60°C) and freezer (T = -10°C) were used to study the effect of temperature change. It was found that when the orientation of the electrical field relative to the direction of compaction was kept constant, the electrical resistivities were independent of the size or shape of samples. Electrical resistivity decreased with increase in compactive effort. Higher resistivity was noted for soil compacted dry of optimum water content. Electrical resistivity shows a rapid decrease with increase in molding water content for dry of optimum water content. Wet of optimum, the electrical resistivity is nearly independent of molding-water content. Each soil displayed a unique interrelation of electrical resistivity and initial saturation which was independent of the compactive effort. At optimum water content, electrical resistivity manifests an inverse relation with temperature, index properties, percentage fines and clay content. A specific relation could not be established for hydraulic conductivity and electrical resistance. At higher molding-water contents the degree of anisotropy decreased. The study recommended further research to understand the effect of anisotropy, electrical anomalies, varying composition and liner boundaries on electrical field and resistivity surveys.

Sirieix *et al.* (2013) used DC electrical methods for defect detection in a geosynthetic clay liner (GCL) in a landfill cap. The experimental site of 1.5-m depth and 12×11 m^2 surface area, from bottom to top, composed of 1-m thick clay layer, 6-mm thick GCL, 300-mm thick artificial gravel layer and 150-mm thick top soil layer. Defects in GLC in the form of tears, holes and overlaps were engineered. Humidity and temperature sensors were installed at depth of 0.7-m below GCL. A weather station was also set up near the site. The results obtained by electrical resistivity tomography (ERT) surveys, using two arrays (dipole-dipole and Wenner - Schlumberger), were compared. Vertical electrical sounding (VES) inversions were used to confirm results and to find real onsite GCL resistivity. It was found that as the layer was very thin (4-7 mm) and highly resistive (100,000 to 2,000,000 Ωm), imaging techniques (ERT) failed to model it properly. However, dipole-dipole array was found to be better than Wenner – Schlumberger array for resistivity resolution of defects. During the initial 21 months, the GCL resistivity range was observed to be 3×10^5 - 4×10^6 Ωm depending on saturation conditions. Later a drop in GCL resistivity range (4×10^4 - $10^5 \Omega m$) reveals probable chemical damage in cover due to aging.

Kodikara & Rahman (2001) refuted the existing practice of using optimum water content (OMC) to specify the field water content for compacted clay liner (CCL) systems. Twelve set of data from previous study for two local soils obtained from different landfill sites was used. Dry unit weight was calculated using the equation (2.5);

$$\gamma_{wet} = (1+w)\gamma_{dry} \tag{2.8}$$

Curves were plotted for wet unit weight (γ_{wet}), dry unit weight (γ_{dry}) and saturated hydraulic conductivity (k_{sat}) against water content (W). Additionally, water content at minimum hydraulic conductivity (w_k) was plotted against optimum water content (w_{opt}) and water content at maximum wet unit weight, to see the linear regression for each. It was found that the water content, which gives maximum wet unit weight, and the minimum hydraulic conductivity show a better correlation than OMC.

2.3 Concluding remarks

Based on the literature review of previous research work pertaining to the chosen area of study, the following specific areas were identified for further investigation:

- Studies involving electrical resistivity measurement of soil samples in the laboratory are very limited. The electrical resistivity is a fundamental property, which can be used to characterise the soil. Therefore, there is a significant requirement for laboratory based electrical resistivity tests.
- There is an absence of correlation of different geotechnical parameters with electrical resistivity of sand, clay and sand-clay mixtures. A recent study has investigated the relationship of relative density with electrical resistivity (Kuranchie *et al.*, 2014) for sand; but the results are limited as the water content has not been considered. The use of water content alone for the evaluation of resistivity can give erroneous results (McCarter, 1984).
- It has been observed that different standards (ASTM, 2011a, 2011b, 2012b, 2015a,

2015b, 2015c; BIS, 1987; BSI, 1990a, 1990b; Standards Australia, 1997) have given methods for the testing of electrical resistivity of soils and leak detection in liners. These standards are not very clear on both the type of metal electrode to be used, and the ranges of input voltage and frequency. Yan *et al.* (2012) studied the change in the electrical resistivity values by varying AC-input frequency from 10^{-3} to 10^{4} Hz; and reported high polarization errors for low frequency values (10^{-3} to 10^{2} Hz). However there is a need for more specific details in this regard, taking into consideration both the water content and also the relative density.

- There is a need for comprehensive study of the effect of permeant on electrical resistivity.
- For landfilling systems located in close proximity to salt water bodies, there is a possibility of leakages across liners as well as seawater intrusion in the landfill base material. Hence, there is scope for a study which focusses on the effect of seawater and seawater-leachate infiltration on the resistivity of landfill foundation material.

CHAPTER 3

MATERIALS AND METHODS

3.1 General

This chapter presents the materials used in this study and their characteristics. In addition, the methodology of the research is explained.

3.2 Materials used

The materials used in this study were sandy soil, distilled water, tap water and three different leachates. Various geotechnical tests were conducted on them as per the relevant Australian standards to determine their basic characteristics. The specified properties are detailed in next sections.

3.2.1 Sand

Perth sandy soil was used for the purpose of this research. It is obtained from quarries in Western Australia (WA). The landfill foundation soil mentioned throughout the thesis refers to the Perth sandy soil as it is used extensively as landfill base material and for other construction purposes in WA. Specific gravity determination (ASTM, 2014b), Particle-size distribution (ASTM 2007, 2014a) and Standard Proctor soil compaction test (ASTM 2012a) were done to determine the basic soil properties. Perth sandy soil was classified as poorly graded sand (SP) as per Unified Soil Classification System (USCS) (ASTM, 2009).

Fig. 3.1 gives the scanning electron microscope (SEM) image for the sandy soil. Fig. 3.2 shows the particle-size distribution curve and Fig. 3.3 gives the compaction curve for the Perth soil. Table 3.1 lists its various physical properties.

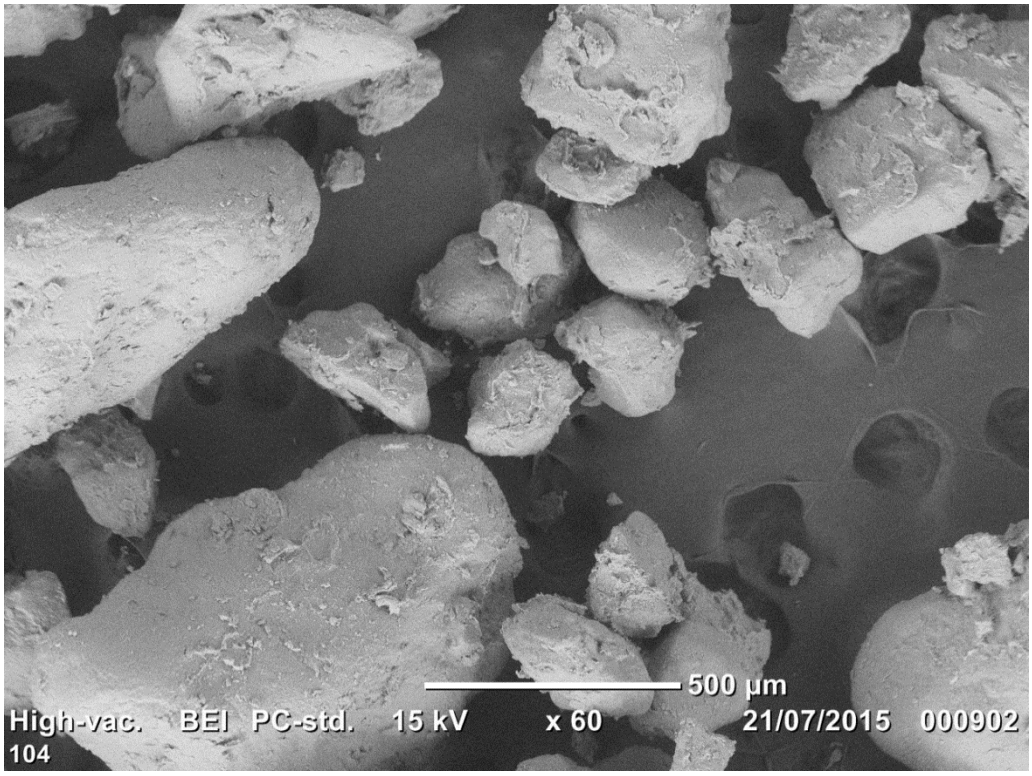

Fig. 3.1 SEM images of Perth sandy soil

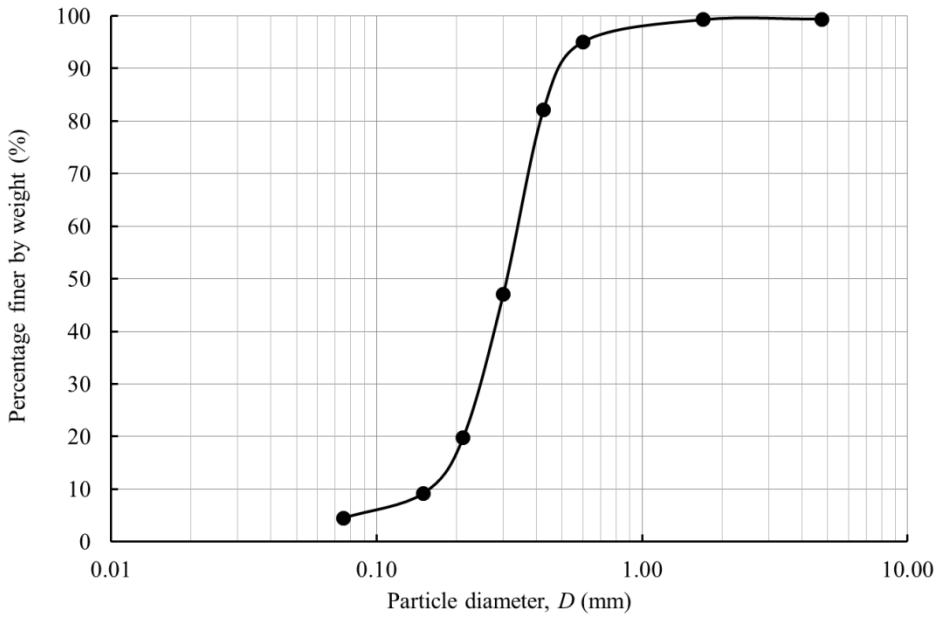

Fig. 3.2 Particle-size distribution curve for Perth sandy soil

Table 3.1 Physical properties of Perth sandy soil

Properties	**Values**
Specific gravity, G_s	2.68
Co-efficient of uniformity, C_u	2.27
Co-efficient of curvature, C_c	1.22
Effective size, D_{10} (mm)	0.15
Minimum dry unit weight , $\gamma_{d\min}$ (kN/m^3)	14.02
Maximum dry unit weight, $\gamma_{d\max}$ (kN/m^3)	15.56
Soil classification as per USCS (Unified Soil Classification System)	Poorly graded sand (SP)

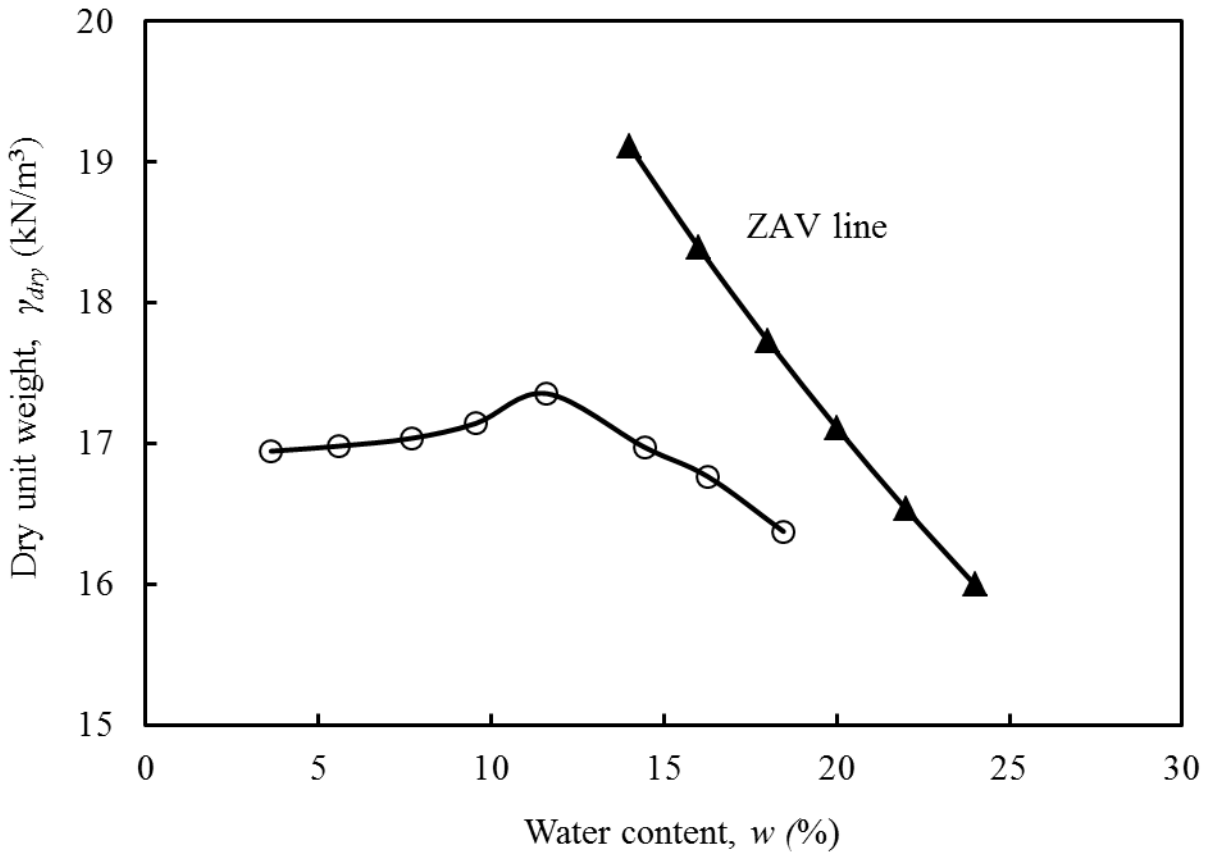

Fig. 3.3 Compaction curve for Perth sandy soil

SEM EDS (energy dispersive x-ray spectroscopy analysis) was used to acquire a comprehensive knowledge of the components of the Perth sandy soil. Fig. 3.4 gives the results obtained by the qualitative analysis of this soil and Fig. 3.5 shows its EDS overlay. It can be seen from Figs. 3.4 and 3.5 that the oxides of silica and aluminium are the major constituents along with trace amounts of carbon.

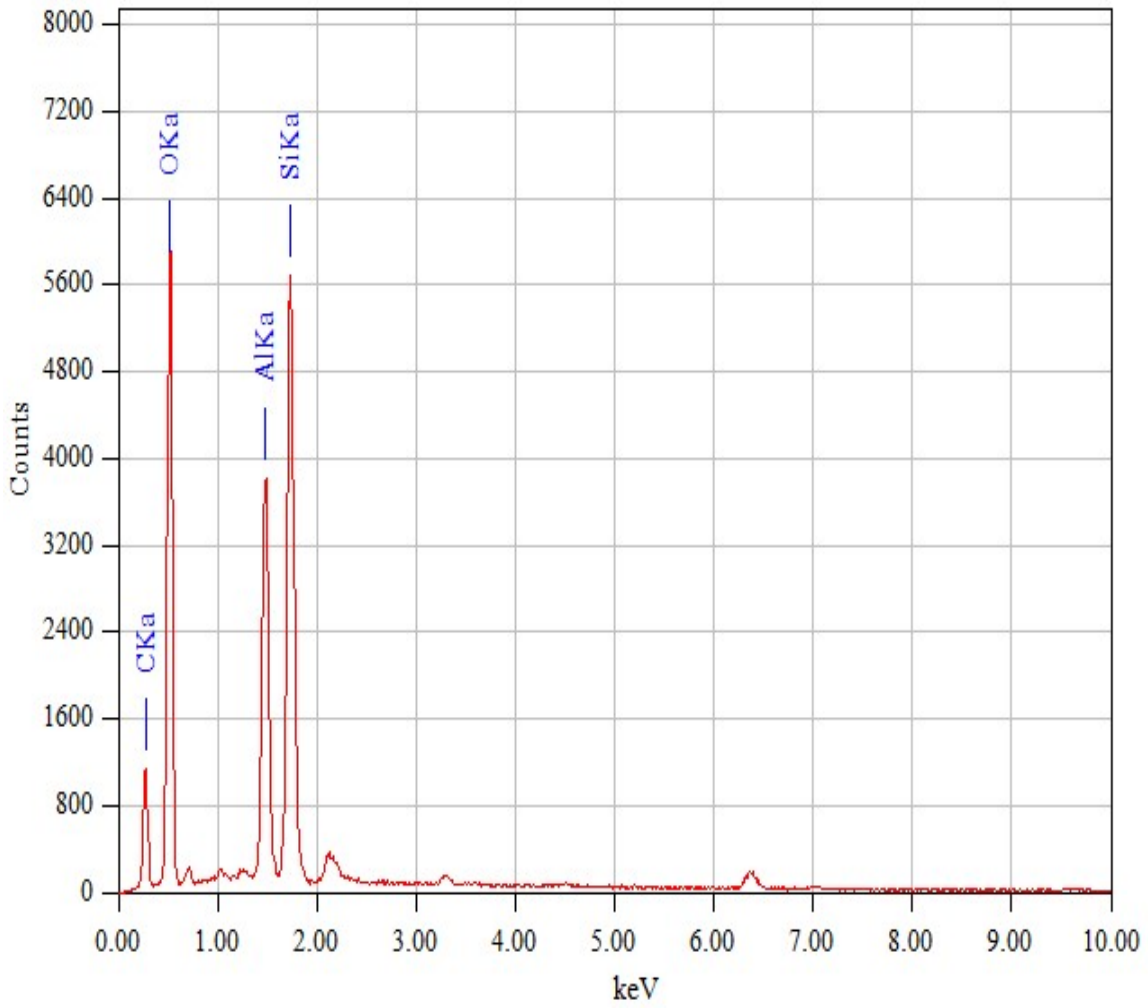

Fig. 3.4 Qualitative analysis of the sandy soil obtained using SEM EDS

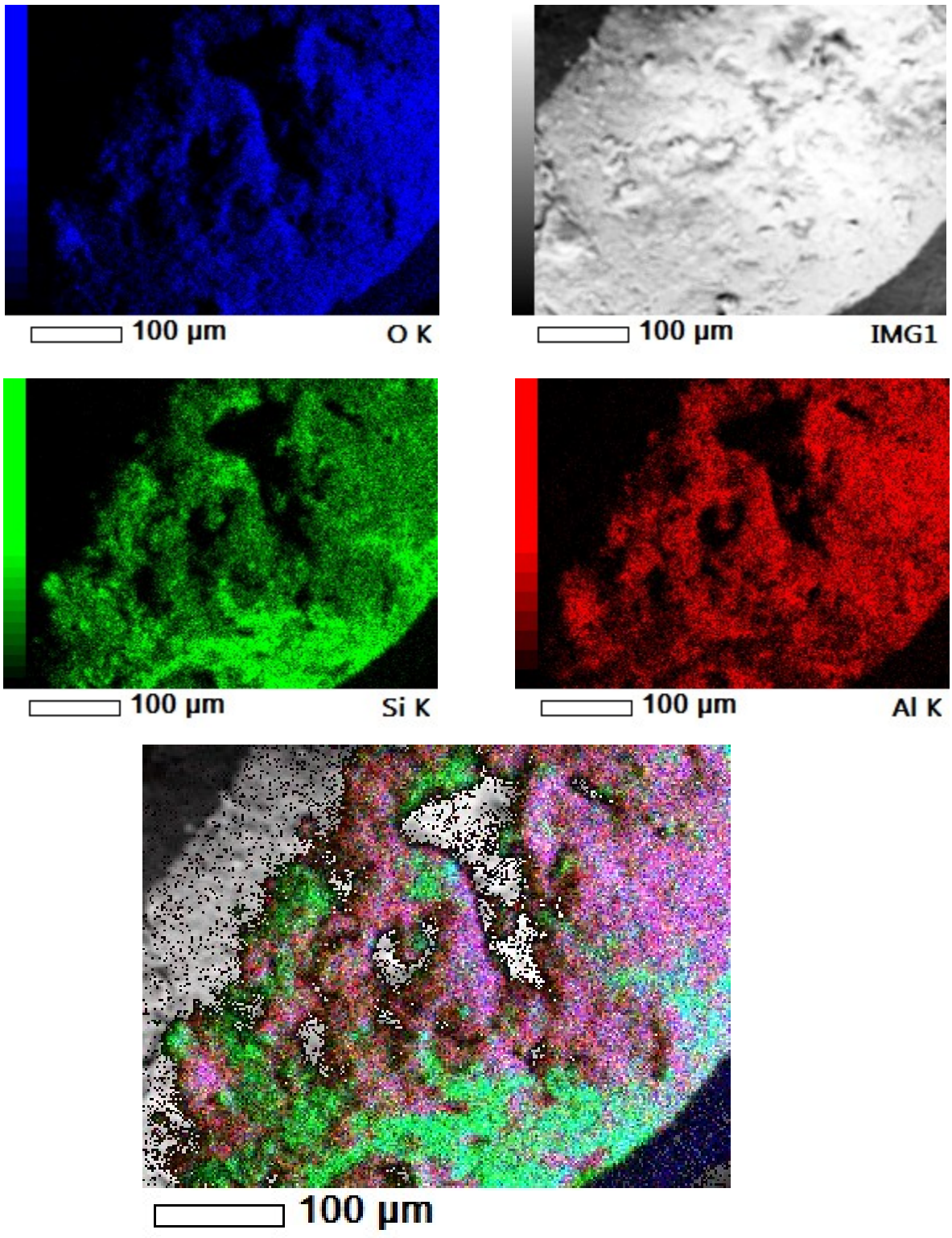

Fig. 3.5 SEM EDS overlay of Perth sandy soil

3.2.2 Water

Two types of water, namely, distilled water and tap water, were used in this research. The distilled water used for the purpose of this study was procured from Refresh Waters Pty Ltd, Malaga, Western Australia (WA). It contains less than 1 ppm of total dissolved solids.

The tap water supplied by Water Corporation, WA to the geotechnical engineering laboratory of Edith Cowan University was used. Table 3.2 lists its various properties.

Table 3.2 Water quality data for tap water (as per Water Corporation, WA)

Properties	**Values**
Alkalinity as $CaCO_3$ (mg/l)	83
Alkalinity as HCO_3 (mg/l)	101
Aluminium acid soluble (mg/l)	0.045
Aluminium unfiltered (mg/l)	0.045
Calcium (mg/l)	28
Chloride (mg/l)	185
Chlorine free residual (mg/l)	0.49
Conductivity (at 25 $^{\circ}$C) (mS/m)	83
Filterable organic carbon (mg/l)	1.8
Hardness as $CaCO_3$ (mg/l)	100
Iron unfiltered (mg/l)	0.02
Magnesium (mg/l)	7.8
Manganese unfiltered (mg/l)	0.002
Nitrate plus nitrite as N (mg/l)	0.45
pH measured in laboratory (dimensionless)	7.86
Potassium (mg/l)	7
Silicon as SiO_2 (mg/l)	17
Sodium (mg/l)	110
Sulphate (mg/l)	29
Total filterable solids (mg/l)	496
True Colour (HU)	<1
Turbidity (NTU)	<0.1

3.2.3 Leachate #1

The first leachate was procured from the Tamala Park landfill waste disposal facility which is operated by the Mindarie Regional Council (MRC), WA. Table 3.3 gives the various properties of Leachate #1 as provided by the MRC. Results are reported on a dry weight basis for solids and on an as received basis for other matrices. Fig. 3.6 shows the Tamala Park landfill site.

Table 3.3 Composition of Leachate #1

Properties	**Unit**	**Value**
pH in water	pH Units	7.9
Electrical conductivity water	µS/cm	26,000
M.B.A.S Methylene blue active substances	mg/L	1.3
Ammonia as N	mg/L	2,200
Nitrate as N	mg/L	<0.5
Total organic carbon	mg/L	1,890
Calcium - dissolved	mg/L	59
Potassium - dissolved	mg/L	1,400
Magnesium - dissolved	mg/L	63
Sodium - dissolved	mg/L	2,000
Bicarbonate HCO_3 as $CaCO_3$	mg/L	11,396
Carbonate CO_3^{2-} as $CaCO_3$	mg/L	<5
Hydroxide OH^- as $CaCO_3$	mg/L	<5
Total alkalinity as $CaCO_3$	mg/L	11,396
Chloride in water	mg/L	2,700
Sulphate in water	mg/L	26
Ionic balance	%	-41
Hardness as $CaCO_3$	mg/L	410

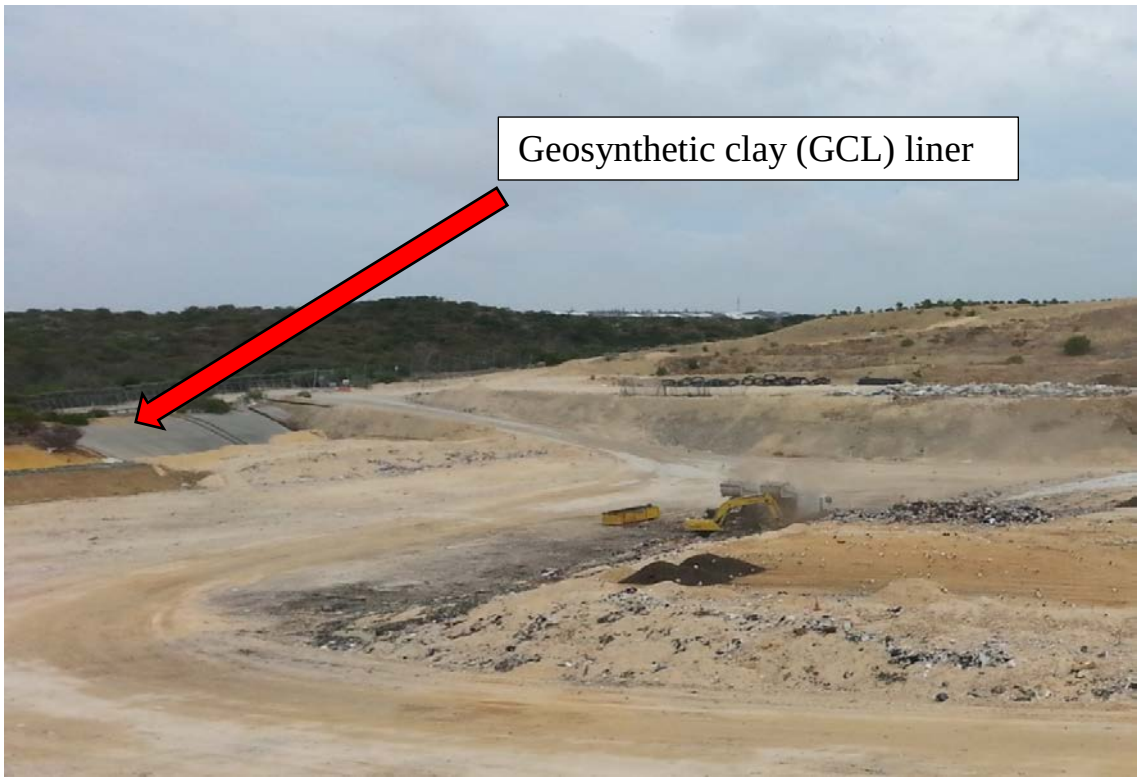

Fig. 3.6 Tamala Park landfilling facility, Mindarie Regional Council (MRC)

3.2.4 Leachate #2

The second leachate was obtained from Iluka Resources, Capel Valley, WA. The company is involved in mineral sand processing. The details of the composition of Leachate #2 named as Iron concentrate pellet feed are shown in Table 3.4.

Table 3.4 Composition of Leachate #2

Properties	**Content**
Ammonium chloride	0.3-6%
Quartz (silica crystalline)	0.1-1 .5%
Magnetite	<70%
Haematite	<15%
Water	<15%
Titanium dioxide	3-5%
Manganese (II) oxide	0.5-2%
Aluminium oxide	0.1-0.8%

3.2.5 Leachate #3

Table 3.5 lists the composition of Leachate #3 (Iron man gypsum (pelletised)/ Nutri sponge/ NUA). Fig. 3.7 shows the empty pond that is used for the collection of leachate generated from mineral sand processing.

Fig. 3.7 Leachate collection pond (Courtesy: Iluka Resources, Capel Valley, WA)

Table 3.5 Composition of Leachate #3

Properties	**Content**
Quartz (silica crystalline)	5%
Calcium sulphate dihydrate	55%
Iron hydroxide	25%
Magnesium hydroxide	2%
Titanium dioxide	2%

3.2.6 Seawater

Seawater was also used in this research. Table 3.6 gives the typical composition of seawater. Fig. 3.8 depicts the collection procedure. The pH of seawater ranges from 7.5 to 8.4 (Chester & Jickells, 2012).

Table 3.6 Typical composition of seawater (adapted from Sverdrup *et al.*, 1942)

MAJOR SOLUTES IN SEAWATER

Salt Ion	Ions in Seawater* (‰)	Ions by Weight (%)	Cumulative (%)
Chloride (Cl^-)	18.980	55.04	55.04
Sodium (Na^+)	10.556	30.61	85.65
Sulfate (SO_4^{2-})	2.649	7.68	93.33
Magnesium (Mg^{2+})	1.272	3.69	97.02
Calcium (Ca^{2+})	0.400	1.16	98.18
Potassium (K^+)	0.380	1.10	99.28
Bicarbonate (HCO_3^-)	0.140	0.41	99.69
Bromide (Br^-)	0.065	0.19	99.88
Boric acid (H_3BO_3)	0.026	0.07	99.95
Strontium (Sr^{2+})	0.013	0.04	99.99
Fluoride (F^-)	0.001	0.00	99.99
Total	34.482	99.99	99.99

Fig 3.8 Collection of seawater (Coogee Beach, Perth, WA)

3.3 Geotechnical tests

The experimental study consisted of basic geotechnical tests such as specific gravity determination and sieve analysis along with compaction test.

3.3.1 Specific gravity determination

Tests were conducted in accordance with ASTM D854-14 (ASTM, 2014b). Specific gravity of solid soils G_s is the mass of a given volume of the mineral solids in soil normalized relative to the mass of an equivalent volume of water. About 60 g of dry soil sample was weighed. A 500-ml flask was filled to the etch mark and the weight was obtained. Half of the water was poured out of the flask and the dried soil sample was poured in the flask with a funnel. Vacuum supply with a gauge pressure of 660 mm Hg (12.8 psi) was connected to the flask for 30 mins for the de-airing of the sample. Distilled water was used to make up the remaining volume of flask till the etch mark. Weight was taken. Also, water temperature in the flask was recorded.

3.3.2 Particle-size distribution

Soils consist of individual particles or grains. Particle-size refers to the size of an opening in a square mesh through which a grain will pass. As all the grains in a soil mass are not same, a gradation curve can be plotted for a specific particle-size and a corresponding percent (by weight) of the soil grains that are smaller than that particle-size. For the sand sample used in this study, mechanical sieving and wet sieve analysis have been used for the particle-size distribution (ASTM 2007, 2014a).

A mechanical sieve analysis involves a nested column of sieves with wire mesh cloth (screen). A representative 750 g sample of aggregate (M_{total}) was poured into the top sieve which had the largest screen openings. Each lower sieve in the column had smaller openings than the one above. At the base was a round pan, called the receiver. The column was placed in a mechanical shaker for 10 mins. After the shaking was completed, the material on each sieve was weighed. The weight of the sample of each sieve was then divided by the total weight to give the percentage retained on each sieve.

Wet sieve analysis was carried out to determine the amount of fines (particle-size less than 75μ corresponding to a #200 sieve) in the soil sample. For wet sieving, the soil was combined with water and sodium hexametaphosphate to disperse the flocculated clay particles so that they could individually pass through the sieve. The slurry was then passed through a #200 sieve to estimate percentage fines in the soil.

3.3.3 Soil classification

Soil was classified as per unified soil classification system (USCS) (ASTM, 2009) based on its engineering properties, including strength, permeability and compressibility. Each soil sharing a common USCS classification was assigned a two-letter group symbol and a group name.

3.3.4 Standard Proctor soil compaction test

The ASTM D698 - 12e2 (ASTM, 2012a) test method for compaction was used to develop a laboratory-derived standard reference density that was used to determine the percentage of compaction and deviation from the optimum water content which was measured by the field in-place density tests.

Compaction is the process by which the bulk density of an aggregate of matter is increased by driving out air. For any soil, for a given amount of compactive effort, the density obtained depends on the water content. At very high water contents, the maximum dry density is achieved when the soil is compacted to nearly saturation, where (almost) all the air is driven out. At low water contents, the soil particles interfere with each other; addition of some moisture will allow greater bulk densities, with a peak density where this effect begins to be counteracted by the saturation of the soil.

The laboratory tests consisted of compacting the soil at a known water content w into a cylindrical mould of standard dimensions using a standard compactive effort of (12,400 ft-lb/ft^3 or 600 kN-m/m^3). The soil was compacted into the mould in three equal layers, each receiving 25 blows from a standard weighted hammer at a specified height. This process was then repeated for various water contents and the dry densities were determined for each. The graphical relationship of the dry density γ_d to water content w was then plotted to establish the compaction curve.

The maximum dry density was finally obtained from the peak point of the compaction curve and its corresponding water content, also known as the optimal water content w_{opt} .

3.3.5 Determination of mineralogy of sand

Scanning electron microscope (SEM) has been used to ascertain the mineralogy for sand and bentonite.

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image. The most common mode of detection is by secondary electrons emitted by atoms excited by the electron beam. By scanning the sample and detecting the secondary electrons, an image displaying the topography of the surface is created.

3.4 Electrical resistivity test

The electrical resistivity of several mixes of the soil was determined by conducting tests in accordance with Australian standard AS 1289.4.4.1-1997 (Standards Australia, 1997): determination of the electrical resistivity of a soil - method for sands and granular materials.

3.4.1 Experimental set-up

As per AS 1289.4.4.1-1997, a resistivity box (as shown in Fig. 3.9) was fabricated using 10-mm thick perspex sheets and fitted with brass electrodes. The dimensions of the box were kept as 220-mm external length, 40-mm internal width and 30-mm internal depth in accordance with the aforementioned standard. A similar box was fabricated with stainless steel in order to investigate the effect of the electrode material on electrical resistivity.

Each resistivity box was fitted with two current plate electrodes, C_1 and C_2. The plate electrodes were of 40-mm width, 30-mm depth and 10-mm thickness each. Two potential

measuring pins P_1 and P_2 were also fitted as shown in Fig. 3.9. The distance between the axes of potential measuring pins, P_1 and P_2, was 120 mm and their diameter was 3 mm.

An AC-input current was chosen for use throughout the study, as AC current reduces polarization effects (McCarter, 1984; Sachs & Spiegler, 1964; Yan *et al.*, 2012). The AEMC 6471 can supply two different voltages (16 & 32 V), across a range of frequency values (55, 92, 110, 119, 128 & 550 Hz), making it ideal for use in this study.

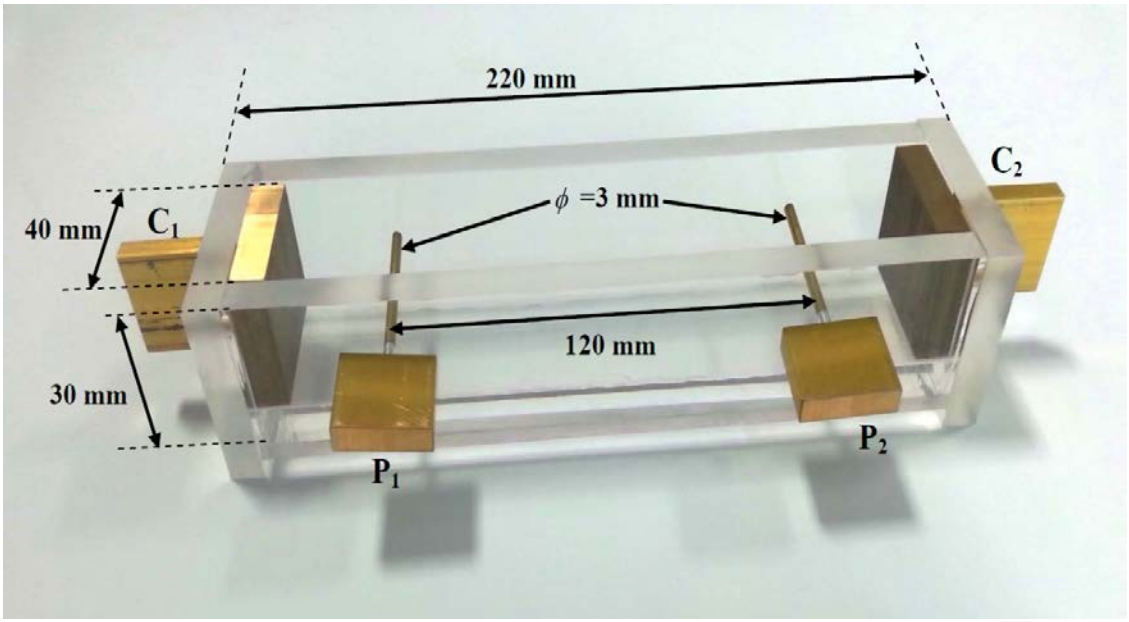

Fig. 3.9 Resistivity box fabricated for the study as per AS 1289.4.4.1-1997

3.4.2 Sample preparation

The sand sample was oven dried at 110 °C overnight before adding the permeant. A known amount of oven-dried soil was mixed with a specific amount of permeating fluid to achieve desired water content. The water content was varied from 4% to 20%. The lower limit of 4% was selected based on previous research which indicated that dry sands exhibit extremely high resistivity values (AS/NZS 1768, 2007; Gupta & Hanks, 1972; Kalinski & Kelly, 1993; Kuranchie *et al.*, 2014; McCarter, 1984; Munoz-Castelblanco *et al.*, 2012; Rhoades *et al.*, 1976; Yan *et al.*, 2012). At water content of 20%, near saturation condition is attained.

The relative density was varied from 0 to 100%. For a fixed value of relative density (D_r) and at specific water content (w), the total unit weight (γ) was calculated using equations given below (Lambe & Whitman, 2008):

$$D_r = \frac{(\gamma_d - \gamma_{d\min})}{(\gamma_{d\max} - \gamma_{d\min})} \frac{(\gamma_{d\max})}{\gamma_d} \times 100 \quad (3.1)$$

$$\gamma = \gamma_d (1 + w) \quad (3.2)$$

where

γ_d is the dry unit weight,

$\gamma_{d\max}$ is the maximum dry unit weight and

$\gamma_{d\min}$ is the minimum dry unit weight.

The amount of sand mixture to be filled in each soil box was determined using the calculated γ and internal volume of the box. The weighed soil sample was divided into three parts and filled in the soil box layer by layer to maintain homogeneity. Three levels were marked on both the boxes to ensure that each soil layer covered approximately one-third of the box volume. Gentle blows with a small compaction tool were given to maintain the level.

3.4.3 Test procedure

Figure 3.10 shows the schematic diagram of the system used to measure the electrical resistivity of the soil sample. The connections between the resistivity testing box filled with soil specimen and the AEMC ground resistance testing machine were made as shown in the figure. The current plate electrodes C_1 and C_2 were connected to the current knobs H and E of the ground resistance tester, respectively. The potential measuring pins P_1 and P_2 were connected to the potential knobs S and ES, respectively.

Current was injected into the soil specimen through the outer plate electrodes. The potential

drop across P_1 and P_2 was determined to calculate the resistance R of the specimen. This four-electrode system was chosen for the test as it has low polarization effects (Campanella & Davies, 1997). Due to the inherent geometry of the resistivity box used in this test, the equation 1.3 to calculate the resistivity ρ of the soil specimen is modified to:

$$\rho = \frac{R}{100} \tag{3.3}$$

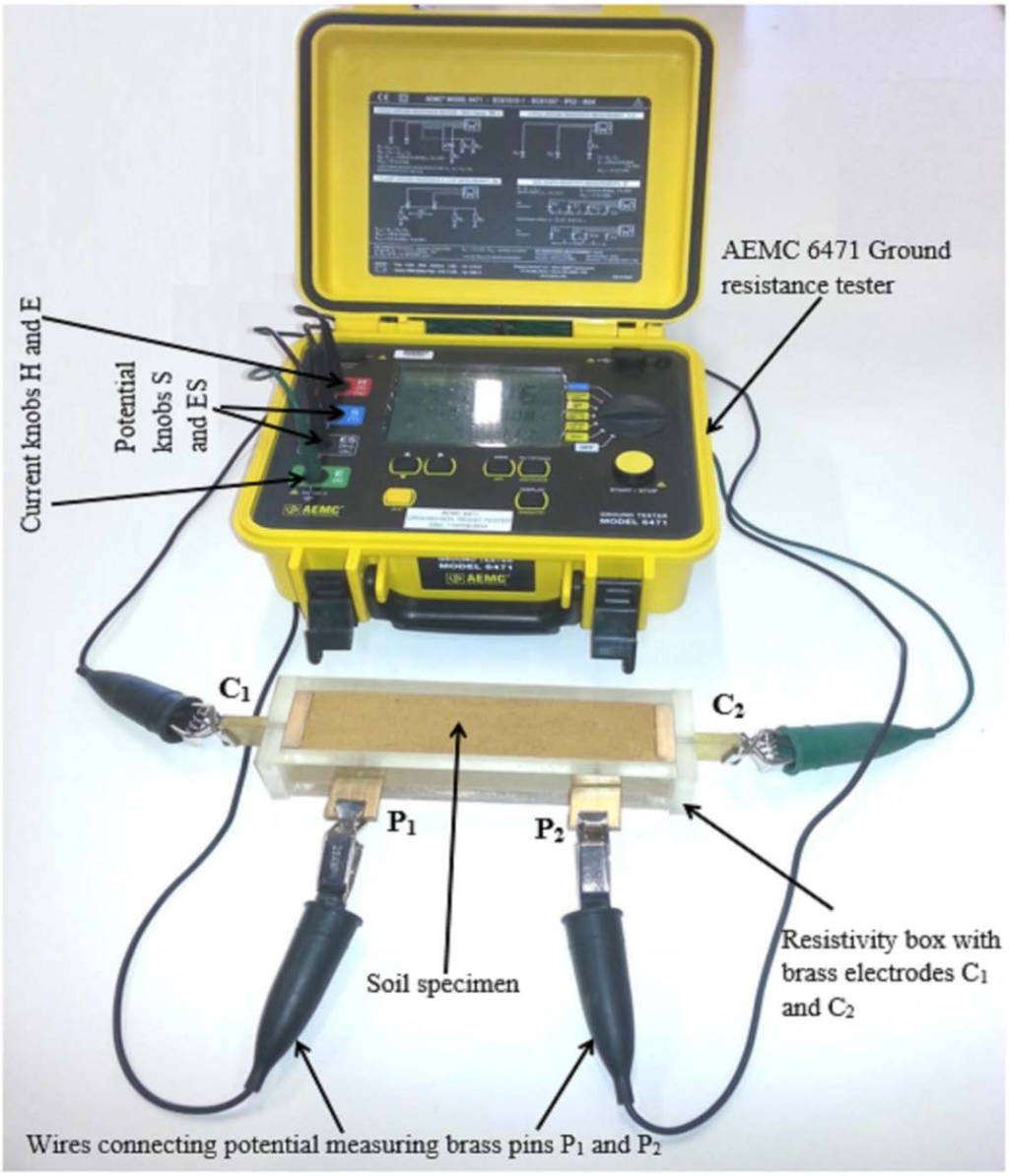

Fig. 3.10 Schematic diagram of the system used to measure the electrical resistivity of the soil sample

Preliminary tests were conducted to investigate the effect of various parameters to determine the areas that needed further scrutiny. Sand specimens at water content of 4% and 16% were made. The electrical resistance was noted for each water content at relative density values of 25% and 75%. Such extremities in value were chosen to account for all possible contingencies. Based on these initial investigations, the input voltage of 16 V and an input frequency of 128 Hz were chosen for further experimentation.

The metal electrodes were cleaned prior to each set of tests (ASTM, 2012b) to counter the effects of electrodeposition (Bicelli et al., 2008) and to produce repeatable readings. The room temperature was maintained at 20°C (Kalinski & Kelly, 1993) in order to avoid the effect of temperature changes on the electrical resistivity during the tests (AS/NZS, 2007).

The effect of choice of electrode material was studied by testing the electrical resistivity of similar soil specimens using two resistivity boxes fitted with brass and stainless steel (SS) electrodes. Distilled water and tap water were used for subsequent resistivity testing. Based on the results of these experiments, empirical correlations were developed for electrical resistivity computation using water content and relative density of soil.

For the purpose of the study of the effect of permeating fluids on the electrical resistivity of Perth sandy soil, three leachates were used as permeants. The relative density D_r was kept fixed at 50% while varying the permeating fluid composition and the water content of the soil mixture. Electrical resistivity readings were recorded as per the aforementioned method and the obtained data was analysed.

Contamination detection in landfilling facilities located close to salt water bodies was also investigated. Electrical resistivity tests were conducted at D_r of 50% while varying the water content w (from 4% to 20%) and the permeating fluid composition (Seawater-Tap water mixture, Leachate #3-Seawater mix, Tap water- Seawater-Leachate #3 mixture).

3.5 Conclusions

The basic soil parameters and composition of Perth sandy soil were established along with procurement of various permeating fluids. Tests were conducted as per AS 1289.4.4.1-1997.

Resistivity boxes fitted with brass and stainless steel electrodes were fabricated. The AEMC 6471 ground resistance tester was obtained for the purpose of the study. The effects of choice of electrode, input voltage and frequency, on resistivity, were scrutinized. Additionally, the effect on the electrical resistivity produced by the gradual changes in water content and relative density of soil mixture was scrutinized. The role of change of permeating fluids was also studied using three leachates. Furthermore, the effect of seawater and seawater-leachate intrusion on the resistivity of landfill base materials was investigated. Based on the obtained results, useful correlations for the electrical resistivity of Perth sandy soils were also developed.

It should be noted that as various fluids have been utilized for this study, hence through this thesis the term ‘water content’ has been interchangeably used with ‘fluid/ permeating fluid content’, especially for different mixes of leachate-tap water-seawater.

CHAPTER 4

ELECTRICAL RESISTIVITY OF SOIL WITH TAP WATER AND DISTILLED WATER

4.1 General

This chapter presents the results of an investigation into the interaction between the various electrical factors pertaining to resistivity tests in Perth sandy soil (specifically AC-input voltage and frequency) and those controlling the soil characteristics, specifically water content and relative density of the soil, and the type of water employed in the tests, whether distilled or tap water. The details presented here are exactly the same as those published in the following paper, as aforementioned in Sec. 1.4:

Pandey, L. M. S., Shukla, S. K. & Habibi, D. (2015). Electrical resistivity of sandy soil. *Geotechnique Letters,* Vol. 5, No. 3, 178–185.

However, the presentation of the material has been altered in accordance with the format of the thesis to maintain uniformity.

4.2 Background

The electrical resistivity of geomaterials is closely related to their geochemical and geotechnical properties, and several relationships between them have been developed in the past (Archie, 1942; Gupta & Hanks, 1972; McCarter, 1984; Kalinski &Kelly, 1993; McCarter & Desmazes, 1997; Fukue *et al.*, 1999). Knowledge of electrical resistivity has been utilised for various purposes, such as defect detection in liners (Sirieix *et al.*, 2013), identification of potential seepage paths (Panthulu *et al.*, 2001), the evaluation of geotechnical parameters of soil (Kalinski & Kelly, 1993), soil salinity (Adam *et al.*, 2012) and corrosiveness (BSI, 1990a) and so on.

Researchers have also investigated the effect of water content and degree of saturation (Archie, 1942; McCarter, 1984; Sreedeep *et al.*, 2004; Munoz-Castelblanco *et al.*, 2012), soil structure (Fukue *et al.*, 1999) and pore fluids (Yoon & Park, 2001) on electrical resistivity of soils. Archie (1942) proposed empirical correlations for the electrical resistivity of a soil with its porosity, degree of saturation and geotechnical properties. Fukue *et al.* (1999) developed an equation for resistivity in terms of the structural coefficient at saturation conditions and other correlations between electrical resistivity and geotechnical parameters for clay and sand–clay mixtures have been investigated by McCarter (1984), McCarter & Desmazes (1997) and Kibria & Hossain (2014). However, the literature presents a lack of experimental results pertaining specifically to the correlation of electrical resistivity of Perth sandy soils with geotechnical parameters such as water content and relative density. A recent study investigated the relationship of relative density with electrical resistivity (Kuranchie *et al.*, 2014) for sand, but the results were limited as water content was not considered. The use of water content alone for the evaluation of resistivity can give erroneous results (McCarter, 1984). Different standards (ASTM, 2011a, 2011b, 2012b, 2015a, 2015b, 2015c; BIS, 1987; BSI, 1990a, 1990b; Standards Australia, 1997) give methods for the testing of electrical resistivity of soils and leak detection in liners, but these standards are not very clear on either the type of metal electrode to be used or the ranges of input voltage and frequency. Yan *et al.* (2012) studied the change in the electrical resistivity values by varying AC-input frequency from 10^{-3} to 10^{4} Hz and reported high polarisation errors for low frequency values (10^{-3} to 10^{2} Hz). However, there is a need for more specific details in this regard, taking into consideration both water content and relative density.

The main purpose of the present work was thus to develop correlations for the electrical resistivity of sandy soil with water content and relative density, focusing specifically on the effects of AC-input voltage and AC-input frequency, electrode material and type of water on electrical resistivity measurements.

4.3 Effect of AC-input voltage and input frequency on resistivity

Tables 4.1-4.4 list the results of the initial resistivity tests on representative soil specimens while investigating the effects of the AC-input voltage and AC-input frequency on the electrical resistivity of the soil. Tables 4.1 and 4.2 provide the results for the brass electrodes while Tables

4.3 and 4.4 provide results for the stainless steel electrodes for extreme conditions of moisture and soil density. The tables show that the water content, relative density and type of permeating fluid have a significant impact on the resistivity of the sandy soil and hence a detailed investigation of these factors was undertaken.

Table 4.1 Effect of AC-input voltage and AC-input frequency on electrical resistivity of sandy soil mixed with distilled water for resistivity box with brass electrodes

AC-input voltage (V)	AC-input frequency (Hz)	Electrical resistivity (Ωm)			
		Sand mixed with distilled water at w = 4%		Sand mixed with distilled water at w = 16%	
		D_r = 25%	D_r = 75%	D_r = 25%	D_r = 75%
32	55	697.3	631.8	244.1	221.4
	92	697.8	632.2	244.7	221.7
	110	698.4	632.5	245.3	222.1
	119	698.7	632.6	245.8	222.8
	128	699.1	632.9	246.2	223.3
	513	699.8	633.2	246.7	223.5
16	55	700.1	633.4	247.0	223.9
	92	700.6	633.7	247.4	224.2
	110	701.1	633.9	247.7	224.6
	119	701.4	634.2	248.3	224.9
	128	701.9	634.3	248.5	225.3
	513	702.2	634.7	248.9	225.6
Average electrical resistivity (Ωm)		699.87	633.28	246.72	223.61
Standard deviation		1.624	0.907	1.537	1.397
Standard error (%)		0.47	0.26	0.44	0.40

Table 4.2 Effect of AC-input voltage and AC-input frequency on resistivity of sandy soil mixed with tap water for resistivity box with brass electrodes

AC-input voltage (V)	AC-input frequency (Hz)	Electrical resistivity (Ωm)			
		Sand mixed with tap water at w = 4%		Sand mixed with tap water at w = 16%	
		D_r = 25%	D_r = 75%	D_r = 25%	D_r = 75%
32	55	543.5	542.8	98.4	91.5
	92	543.7	543.1	98.5	91.8
	110	544.0	543.6	98.8	92.3
	119	544.2	544.2	99.2	92.6
	128	544.4	544.4	99.4	93.0
	513	544.8	544.8	99.8	93.4
16	55	545.1	545.5	100.1	93.6
	92	545.3	545.9	100.5	94.2
	110	545.6	546.2	101.0	94.7
	119	545.9	546.5	101.3	95.2
	128	546.4	546.8	101.6	95.3
	513	546.7	547.2	101.8	95.8
Average electrical resistivity (Ωm)		544.97	545.08	100.03	93.62
Standard deviation		1.048	1.483	1.207	1.433
Standard error (%)		0.30	0.43	0.35	0.41

Table 4.3 Effect of AC-input voltage and AC-input frequency on electrical resistivity of sandy soil mixed with distilled water for resistivity box with stainless steel electrodes

AC-input voltage (V)	AC-input frequency (Hz)	Electrical resistivity (Ωm)			
		Sand mixed with distilled water at w = 4%		Sand mixed with distilled water at w = 16%	
		D_r = 25%	D_r = 75%	D_r = 25%	D_r = 75%
32	55	676.3	628.4	238.9	221.0
	92	676.6	628.6	239.2	221.3
	110	676.9	628.9	239.5	221.7
	119	677.2	629.3	239.8	221.9
	128	677.5	629.5	240.3	222.4
	513	677.8	629.8	240.9	222.8
16	55	678.1	630.2	241.7	223.1
	92	678.4	630.7	242.2	223.5
	110	678.7	631.1	242.6	224.0
	119	679.2	631.5	242.9	224.6
	128	679.4	631.7	243.5	225.2
	513	679.8	632.0	243.7	225.7
Average electrical resistivity (Ωm)		677.99	630.14	241.27	223.10
Standard deviation		1.140	1.249	1.722	1.538
Standard error (%)		0.33	0.36	0.50	0.44

Table 4.4 Effect of AC-input voltage and AC-input frequency on electrical resistivity of sandy soil mixed with tap water for resistivity box with stainless steel electrodes

AC-input voltage (V)	AC-input frequency (Hz)	Electrical resistivity (Ωm)			
		Sand mixed with tap water at w = 4%		Sand mixed with tap water at w = 16%	
		D_r = 25%	D_r = 75%	D_r = 25%	D_r = 75%
32	55	554.1	552.9	95.9	86.8
	92	554.3	553.5	96.4	87.3
	110	554.6	554.1	97.1	87.7
	119	555.2	554.5	97.4	88.2
	128	555.5	554.8	97.7	88.6
	513	555.8	555.2	98.3	89.1
16	55	556.3	555.8	98.6	89.5
	92	556.9	556.3	99.2	89.8
	110	557.2	556.7	99.7	90.1
	119	557.6	557.2	100.1	90.7
	128	558.0	557.6	100.3	91.2
	513	558.4	558.1	100.6	91.9
Average electrical resistivity (Ωm)		556.16	555.56	98.44	89.24
Standard deviation		1.469	1.665	1.570	1.589
Standard error (%)		0.42	0.48	0.45	0.46

The preliminary test results (Tables 4.1–4.4) also indicate that the electrical resistivity of the sandy soil shows a negligible variation (less than 0·5%) corresponding to changes in AC-input voltage and frequency. This observation may not be true for clayey soils.

For the sand mixtures with a distilled water content of 4% at a relative density of 75% (Table 4.1), the electrical resistivity was found to be in the range of 633·28±1·5 Ωm, with a standard deviation of 0·907 Ωm. Similar observations were made in other cases. Hence, a

specific AC-input value may be fixed for carrying out detailed investigation. Since an AC-input voltage of 16 V is an easily attainable supply and has a lower risk than when using 32 V, a 16 V AC supply was used for subsequent studies.

Researchers such as McCarter & Desmazes (1997) advocate the use of a low-frequency (<100 kHz) AC supply to undertake electrical resistivity measurements. In addition, Yan *et al.* (2012) report that tests for electrical properties at low frequencies (10^{-3}–10^{2} Hz) are subject to very high polarisation errors (>100% for some cases). As a consequence of this prior work, an optimum frequency value of 128 Hz was selected.

4.4 Effect of water content on resistivity

Figure 4.1(a) shows how the resistivity measurements vary with changing water content when employing the resistivity box fitted with brass electrodes. Figure 4.1(b) gives the results for similar tests using stainless steel electrodes. It is apparent that the resistivity of sandy soil decreases rapidly with an increase in water content, but the rate of decrease reduces considerably for water contents over 12% for distilled water and 10% for tap water (Figures 4.1(a) and 4.1(b)), irrespective of relative density. For water content greater than about 16%, which corresponds to the onset of saturation conditions in the soil, the resistivity tends to become almost constant. These observations can be explained by the well-established fact that dry sand has extremely high electrical resistivity (Fukue *et al.*, 1999; AS/NZS, 2007; Munoz-Castelblanco *et al.*, 2012). Consequently, the electrical resistivity of sandy soil is primarily dependent upon the amount of permeating fluid, porosity and pore continuity (Yoon & Park, 2001). Hence, even for a slight increase in water content, the resistivity shows a sharp decrease. These observations are in keeping with published results of previous research (Archie, 1942; Gupta & Hanks, 1972; McCarter, 1984; Kalinski & Kelly, 1993; Yoon & Park, 2001; Munoz-Castelblanco *et al.*, 2012; Yan *et al.*, 2012).

Although similarities exist between the graphs of the measurements taken when using brass and stainless steel electrodes (Figs 4.1(a) and 4.1(b), respectively), the curves are not identical due to differences in composition and electrolytic content of the permeating fluids.

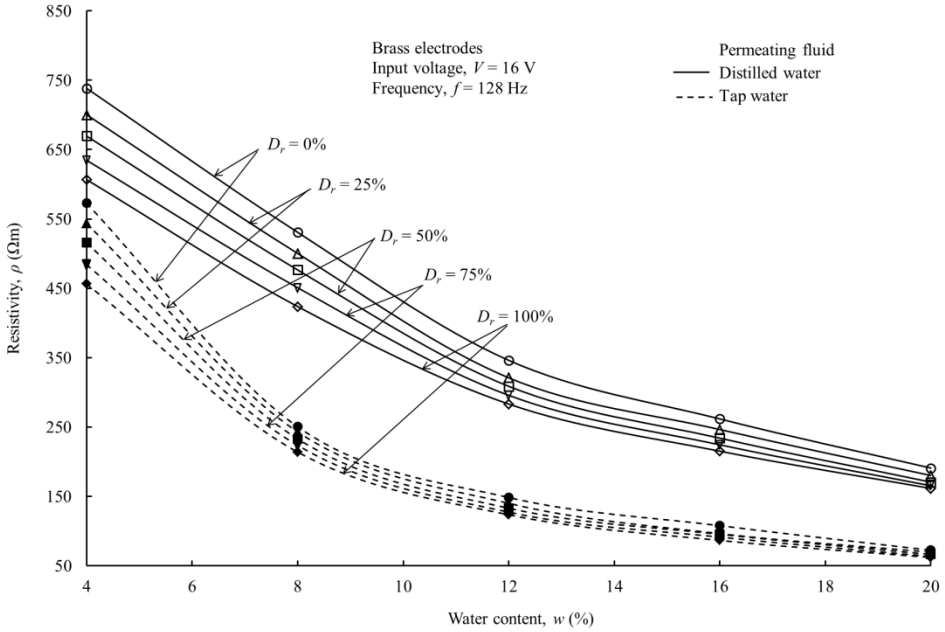

Fig. 4.1(a) Variation of resistivity with water content for box fitted with brass electrodes with both permeating fluids

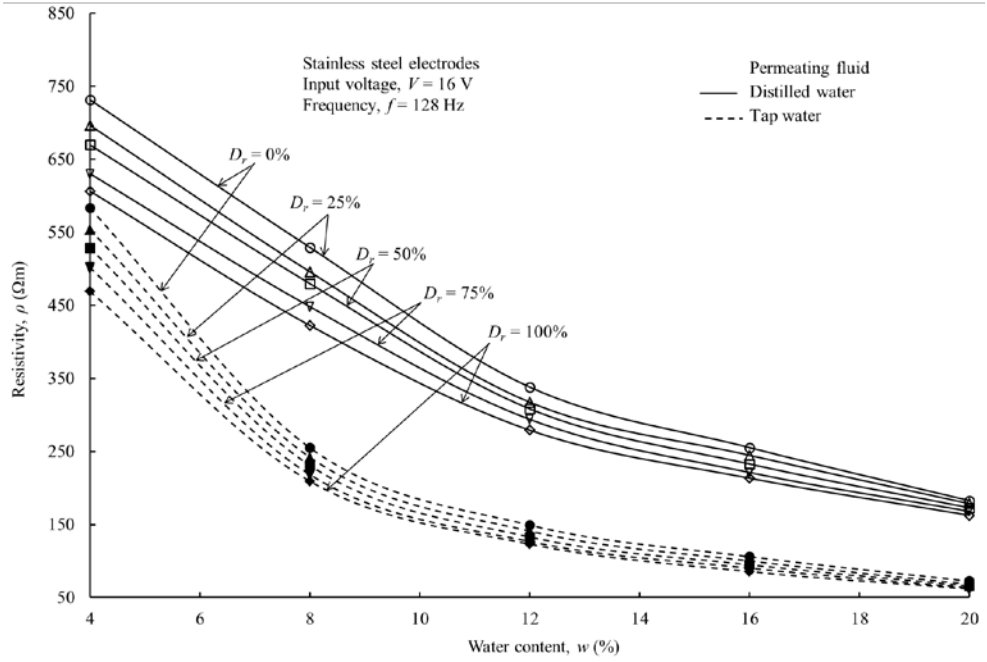

Fig. 4.1(b) Variation of resistivity with water content for box fitted with stainless-steel electrodes with both permeating fluids

It can be observed that the electrical resistivity of distilled water is greater than that of tap water at the same w and D_r. For example at w=8% and D_r=25%, the resistivity of the sand mixture moistened with distilled water was $500 \cdot 20\,\Omega\text{m}$, while for tap water it was $242 \cdot 90\ \Omega\text{m}$ (Fig. 4.1(a)). This disparity is because the tap water contains more ions (Table 3.2) and hence is more conductive than distilled water. The greater presence of ions also accounts for the observation that the changes in electrical resistivity produced by a gradual increase in tap water content are more pronounced than the changes due to increases in distilled water content. It can thus be inferred that the type of permeant has quite a significant impact on the electrical resistivity of sandy soil.

4.5 Effect of relative density on resistivity

Figures 4.2(a) and 4.2(b) show the variation in electrical resistivity with changes in the relative density of sand mixed with distilled water and tap water respectively.

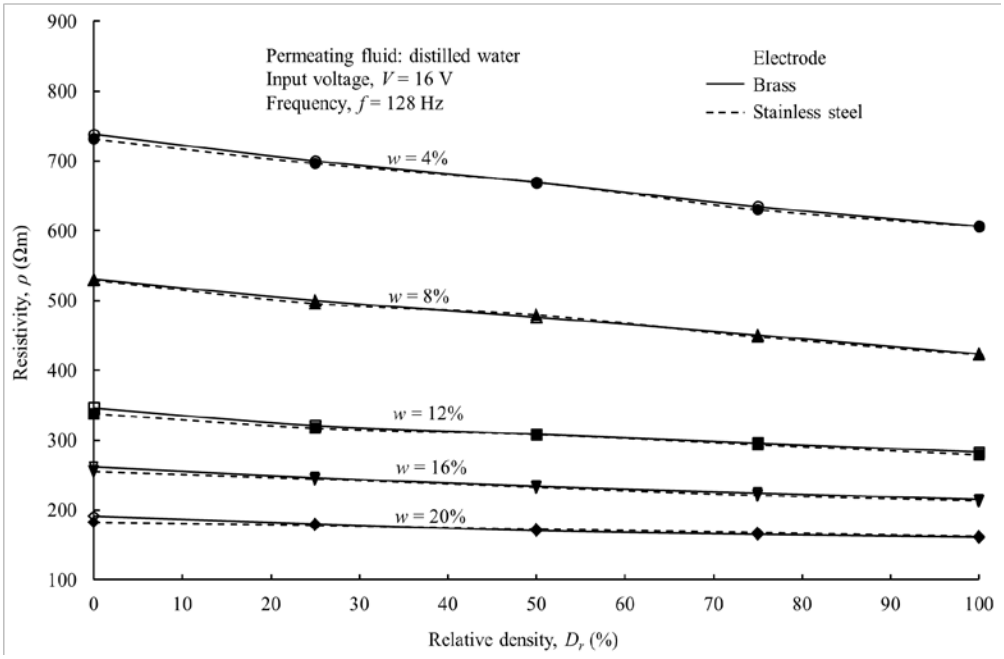

Fig. 4.2(a) Variation of resistivity with relative density for both electrodes with distilled water as permeating fluid

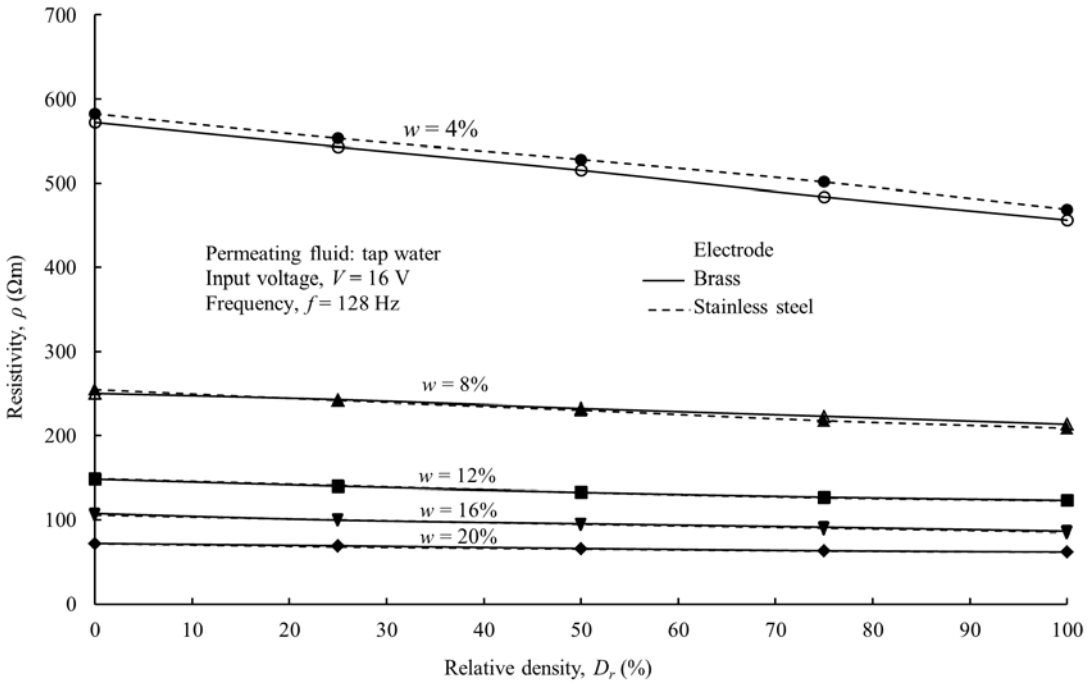

Fig. 4.2(b) Variation of resistivity with relative density for both electrodes with tap water as permeating fluid

It can be seen that, for any value of water content from 4 to 20%, the resistivity decreases almost linearly with an increase in relative density for both permeants. This observation is supported by the fact that, with an increase in relative density of the sandy soil specimen, particle contact and pore continuity is improved. The improved particle contact and pore continuity enable a better current flow path to be established, resulting in the observed decrease in resistivity. It is also evident that any changes to the electrical resistivity of the soil arising from changes in relative density are more pronounced when the water content is lower. In other words, the effect of relative density on electrical resistivity is negligible for higher water contents.

4.6 Effect of electrode material on resistivity

Figures 4.2(a) and 4.2(b) show that the variations in electrical resistivity with changing D_r were

similar for both the resistivity boxes. For a sand mixture with a distilled water content of 20% and relative density of 0%, the resistivity was 190·90 Ωm for brass electrodes and 182·47 Ωm for steel electrodes. It can therefore be inferred that the effect of choice of electrode materials in this experiment was negligible.

4.7 Development of correlations

Using regression analysis, the variation of resistivity ρ (Ωm) of the sandy soil with relative density D_r (%) and water content w (%) can be represented by

$$\rho = 527\left(4.9 - \frac{D_r}{100}\right)(w)^{-0.832} \tag{4.1}$$

for the distilled water, and

$$\rho = 732\left(4.6 - \frac{D_r}{100}\right)(w)^{-1.258} \tag{4.2}$$

for the tap water.

Equations (4.1) and (4.2) show a trend similar to that reported in the previous study conducted by Archie (1942). A generalized equation for the resistivity of the sandy soil can be given as:

$$\rho = c_1\left(c_2 - \frac{D_r}{100}\right)(w)^{-c_3} \tag{4.3}$$

where c_1 (Ωm), c_2 (dimensionless) and c_3 (dimensionless) are specific constants corresponding to a particular soil type and permeating fluid.

Fig. 4.3 compares the variations of resistivity values with water content, obtained from the experiments and equations (4.1) and (4.2) for a specific set of test parameters. It may be noted in

this case that the correlation coefficients are -0.915 and -0.881 for distilled water (equation (4.1)) and tap water (equation (4.2)), respectively.

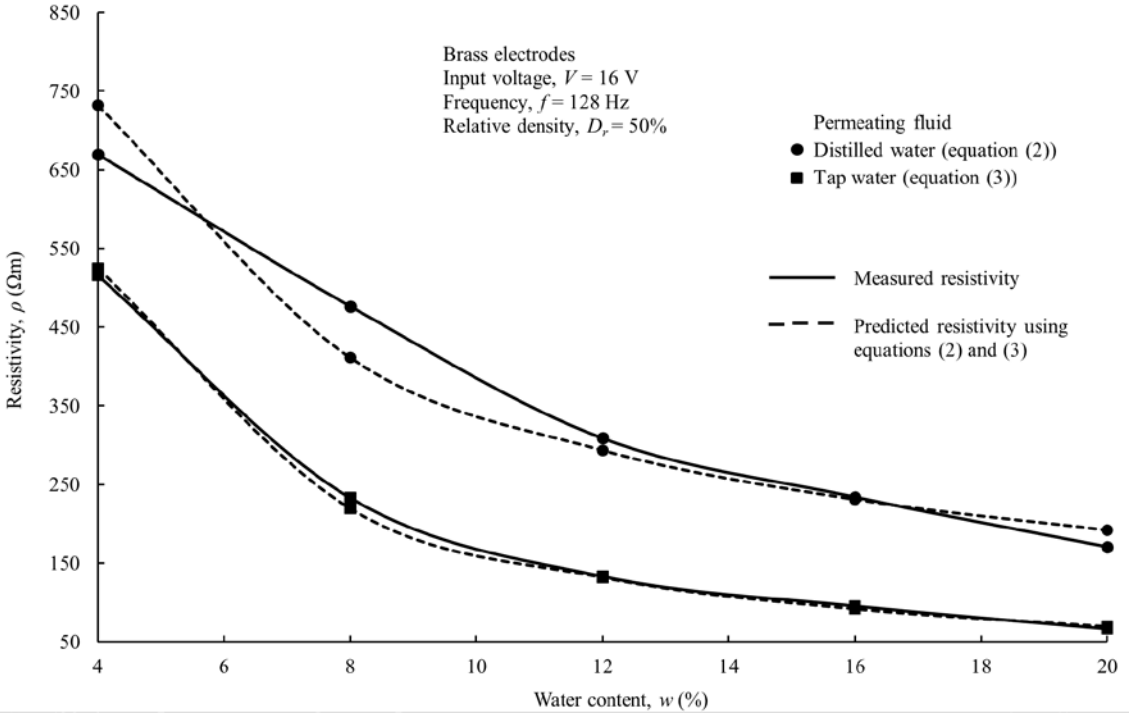

Fig. 4.3 Comparison of measured resistivity value with values predicted using equations (2) and (3)

4.8 Conclusions

The electrical resistivity of Perth sandy soil was found to be independent of the AC-input voltage and frequency within the ranges used in this study. The resistivity of the sandy soil decreased rapidly with an increase in water content, but the rate of decrease reduced considerably for water contents over 12% in the case of distilled water and 10% for tap water, irrespective of the relative density. The resistivity showed an almost linear decrease with a corresponding increase in relative density. The effect of varying relative density on resistivity diminished progressively with an increase in water content. The type of permeating fluid used had a significant effect on resistivity whereas the electrode material had a negligible impact on electrical resistivity measurements for the given test duration. For the sandy soils, relative density and water content

can be used to predict electrical resistivity and vice versa. It is important to note that the findings reported here should not be extrapolated to soils significantly different from the sandy soil used in this study. Furthermore, the experimental simplifications made in the present study should be kept in mind while using the results reported here in field projects.

CHAPTER 5

ELECTRICAL RESISTIVITY OF SOIL WITH LEACHATES

5.1 General

Leachates and other liquid effluents have much higher electrical conductivity compared to the landfill base materials. Hence, the addition of even a small amount of liquid effluent alters electrical properties of geomaterials. This change can be detected easily by the use of the electrical resistivity method. This chapter investigates the effect on resistivity caused by varying leachate type and amount.

5.2 Background

Soil contamination can be achieved in an expeditious manner and at low cost by the use of electrical resistivity method. This method primarily makes use of the well-established fact that liquid effluents like landfill leachates or other industrial wastes possess extremely high conductivity (Yoon & Park, 2001). In comparison, soils have very high electrical resistivity (Fukue *et al.*, 1999; Munoz-Castelblanco *et al.*, 2012) which gets altered by addition of even a small amount of contaminant (Darayan *et al.*, 1998; Yoon & Park, 2001). This change can be readily detected using the electrical resistivity method.

While many previous researches have focused on the use of the changes in electrical properties of soil for the detection of contamination; not much work has been done to observe the changes in resistivity produced by gradually increasing the amount of contaminant. This section highlights the effect on the electrical resistivity of Perth soil specimen produced by gradually changing the leachate content. As Perth terrain possesses mainly sandy soil, contamination detection by the use of the electrical resistivity method is significantly viable. New correlations have been also been developed and presented for the leachates used in this study. The results

obtained by these studies can find application in the development of sensors for landfill leakage detection and location.

Three leachate samples have been used for the purpose of the study. Varying amounts of Leachate #1, Leachate #2 and Leachate #3 (0% to 100% by volume), denoted by A_l, were mixed with tap water and this mixture was used as the pore fluid. Tap water was used as a representation of groundwater. For each fluid mixture, the permeating fluid content/ water content w_{pf} was increased from 4% to 16% and corresponding electrical resistivity readings were obtained. This range was chosen based on aforementioned previous experimentation and observation (Chapter 4). Additionally, it had been observed that the relative density D_r exhibits limited effect on electrical resistivity compared to the water content. Hence, D_r was kept fixed at 50% for the experiments.

It should be noted that in this chapter, various mixes of leachates and tap water have been used as the pore fluid. Hence, water content has been replaced by permeating fluid content/ fluid content.

5.3 Effect of permeating fluid content on resistivity

Figures 5.1 through 5.3 give the variation of the electrical resistivity of the soil with increase in the pore fluid content. It can be observed that for any permeating fluid content, the resistivity exhibits the highest values when A_l is 0%. In other words, the resistivity of sand mixed with tap water alone is considerably greater than when leachate is added to the permeating fluid. This observation is as per expectation as the tap water contains much lower amount of electrolytes (Table 3.2) compared to the three leachates (Tables 3.3 through 3.5). Additionally, this reinforces the aforementioned fact that when liquid effluents permeate geomaterials, they alter their electrical properties. Hence, by detecting these changes, contamination of soils can be effectively determined.

However, it can be noted from Figs. 5.1 through 5.3 that as the fluid content increases, the change in resistivity caused by increasing A_l, is reduced.

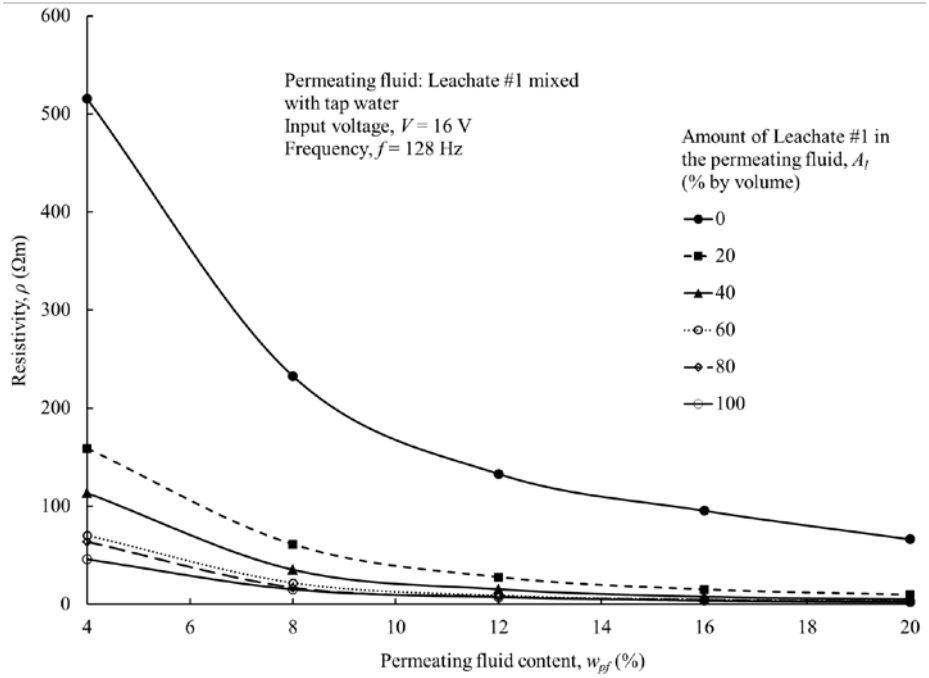

Fig. 5.1 Variation of resistivity with permeating fluid content with Leachate #1 mixed with tap water as permeating fluid

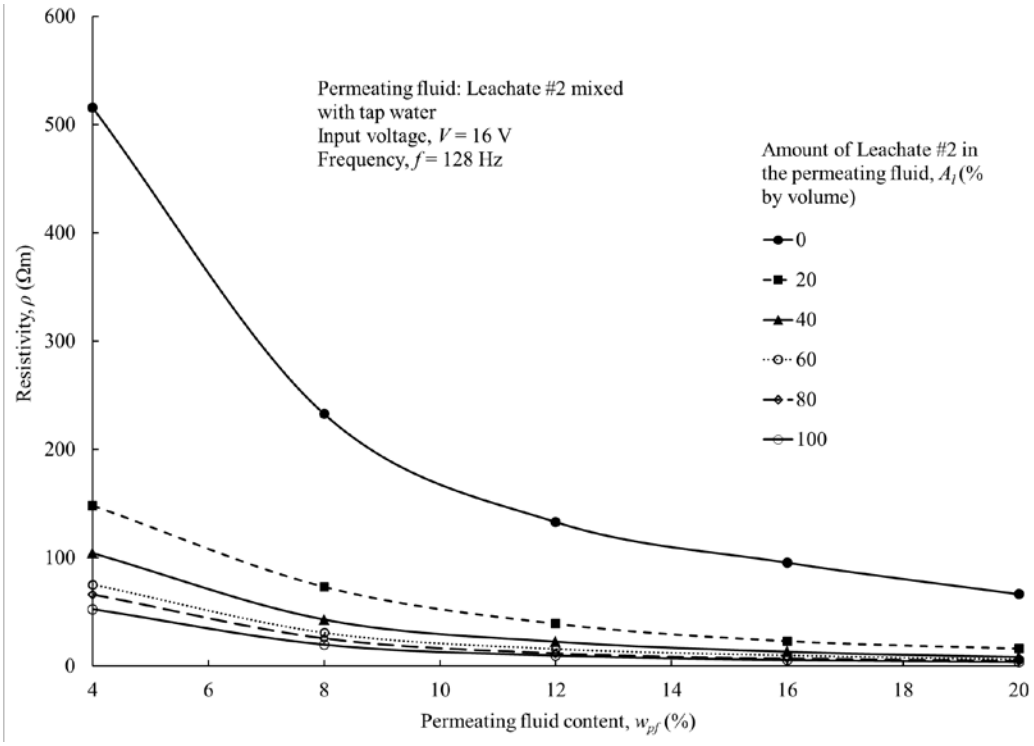

Fig. 5.2 Variation of resistivity with permeating fluid content with Leachate #2 mixed with tap water as permeating fluid

It can be observed (Figs. 5.1 through 5.3) that an increase in the permeating fluid content results in a decrease in the electrical resistivity. The resistivity ρ shows a rapid decrease initially with increase in w_{pf}. However for w_{pf} greater than 9%, the change in resistivity becomes more gradual. For example from the curve of A_l = 20% (Fig. 5.1), the rate of decrease in resistivity for w_{pf} from 6% to 8% is 21.86 Ωm. The rate of decrease of resistivity becomes 6.09 Ωm for w_{pf} from 10% to 12%. This observation is more pronounced at lower A_l. Furthermore, it can be noted from the figures that for all the three leachates the turning point of the curve is nearly same; at the fluid content of 9%.

It can also be seen from the Figures 5.1 through 5.3 that for w_{pf} greater than 16%, which is near saturation condition of the soil, the resistivity becomes nearly constant

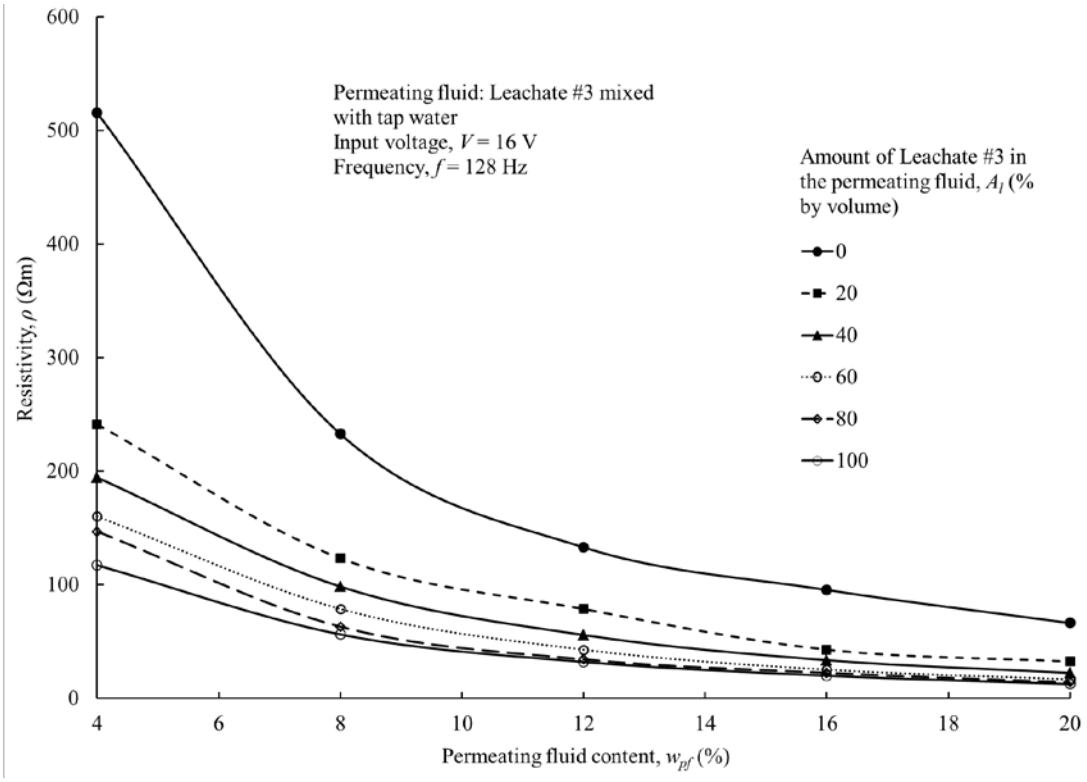

Fig. 5.3 Variation of resistivity with permeating fluid content with Leachate #3 mixed with tap water as permeating fluid

5.4 Effect of amount of leachate in the permeating fluid

Figures 5.4 through 5.6 gives how the electrical resistivity varies with the amount of leachate in the permeating fluid (A_l).

It is immediately apparent that the nature of the curves is similar for the three leachates. The resistivity shows a rapid decrease with increase in A_l. The rate of decrease is significantly lowered for A_l greater than 20%. Additionally for Leachates #1, #2 and #3, it is interesting to note that the curves indicate a point of inflection at A_l = 30%.

When the amount of leachate added to the permeating fluid exceeded 20%, insignificant decrease in resistivity was observed, irrespective of the pore fluid content w_{pf} in the sand mixture.

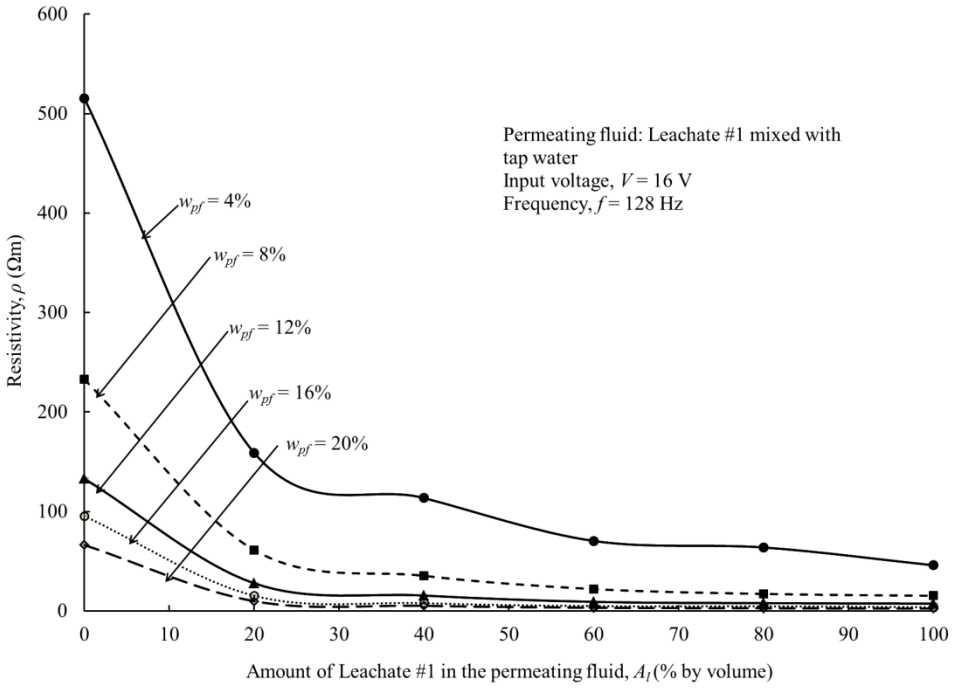

Fig. 5.4 Variation of resistivity with the amount of Leachate #1 in the permeating fluid, A_l (% by volume)

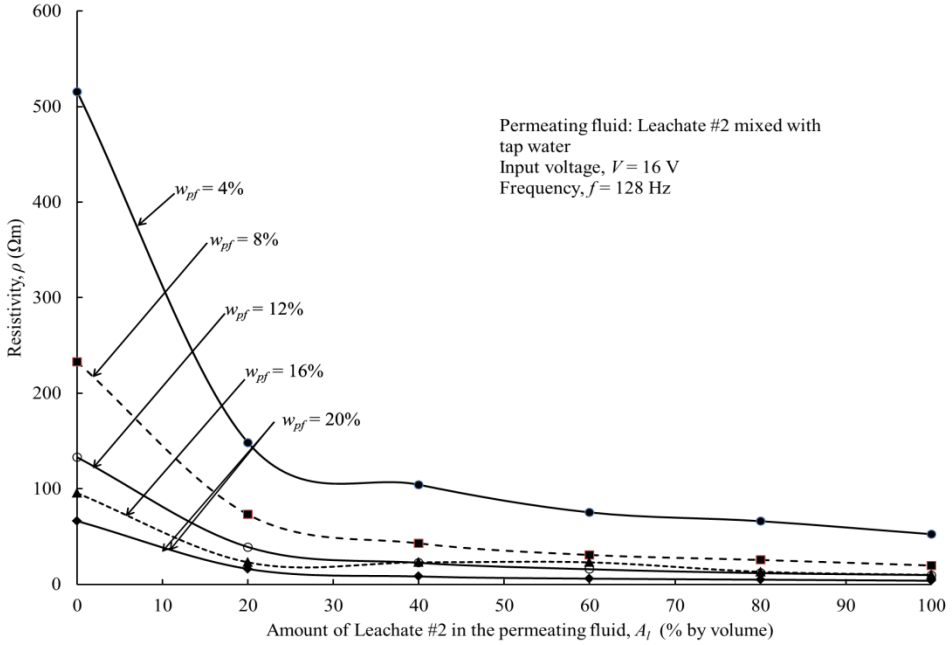

Fig. 5.5 Variation of resistivity with the amount of Leachate #2 in the permeating fluid, A_l (% by volume)

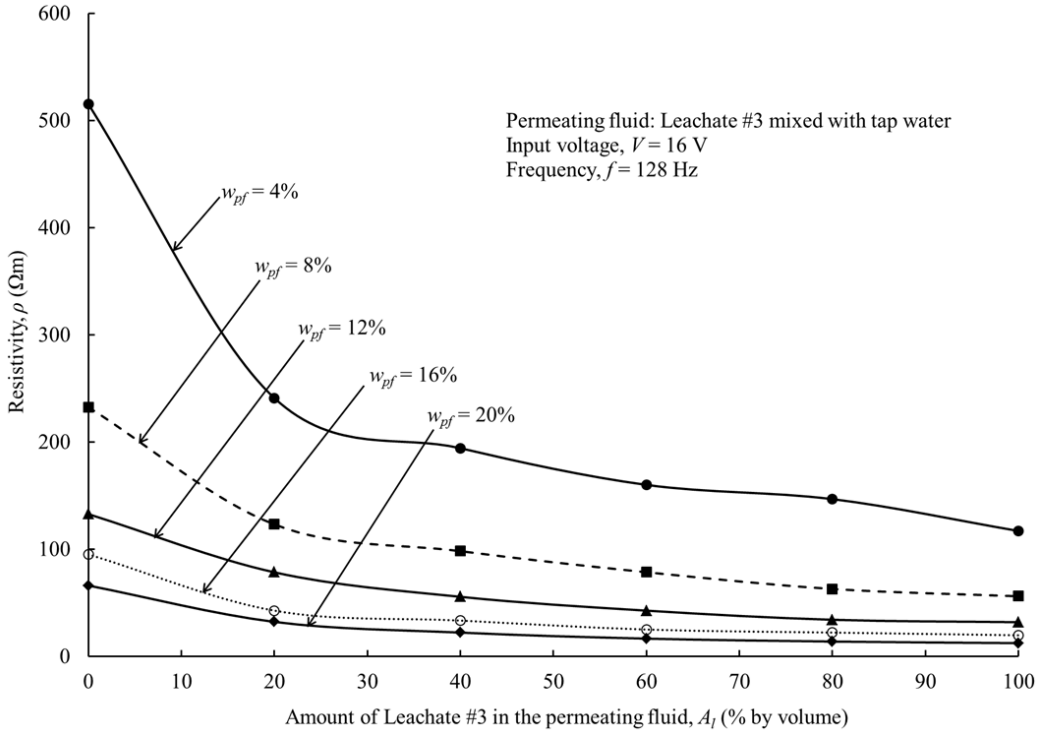

Fig. 5.6 Variation of resistivity with the amount of Leachate #3 in the permeating fluid, A_l (% by volume)

Furthermore, at higher values of w_{pf} (greater than 8%) the resistivity was found to become nearly steady. Consequently, it can be inferred that at higher fluid contents, the effect of amount of leachate becomes negligible. In other words, the effect of changing A_l is more significant at lower w_{pf} .

5.5 Comparison of Leachate #1, Leachate #2 and Leachate #3

Figures 5.7 through 5.11 compare the resistivity values measured by gradually increasing the amount of Leachates #1, #2 and #3 in the permeating fluid. Figure 5.7 gives the results obtained by using a permeating fluid content w_{pf} of 4%. Figs. 5.8 through 5.11 give similar results for w_{pf} of 8%, 12%, 16% and 20%.

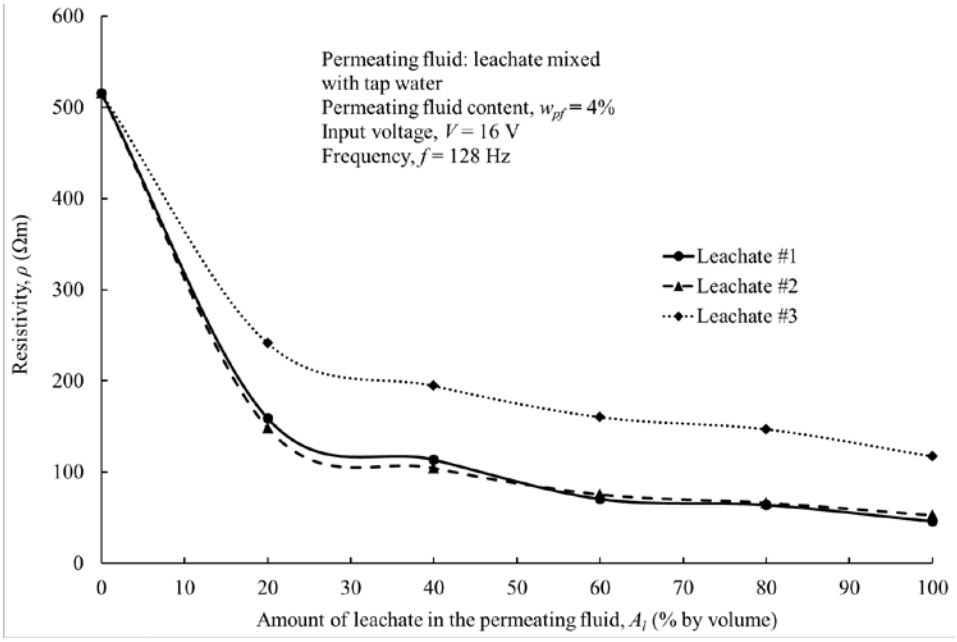

Fig. 5.7 Comparison of Leachate #1, Leachate #2 and Leachate #3 at permeating fluid content of 4%

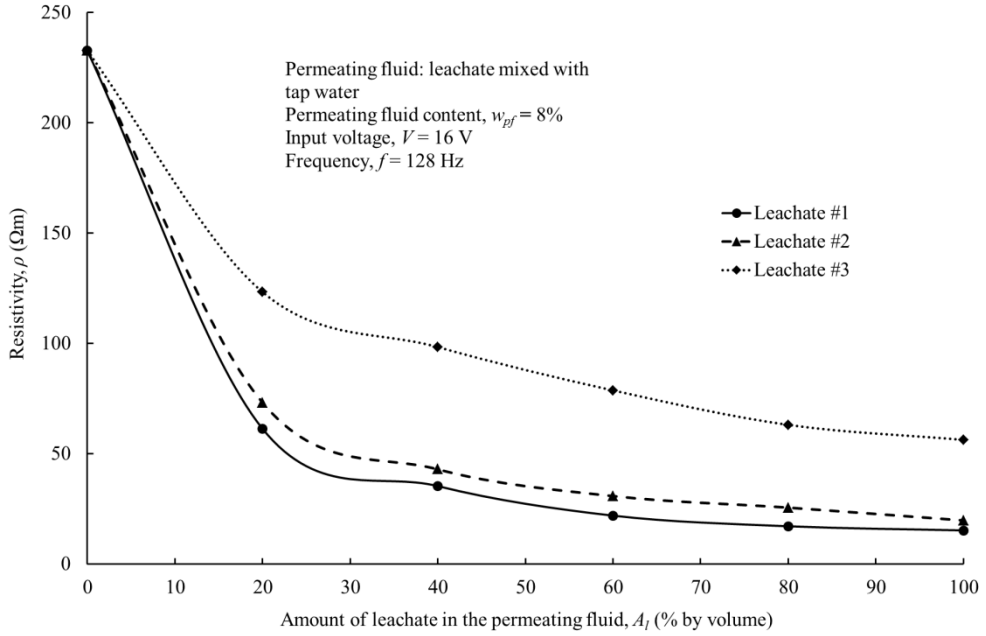

Fig. 5.8 Comparison of Leachate #1, Leachate #2 and Leachate #3 at permeating fluid content of 8%

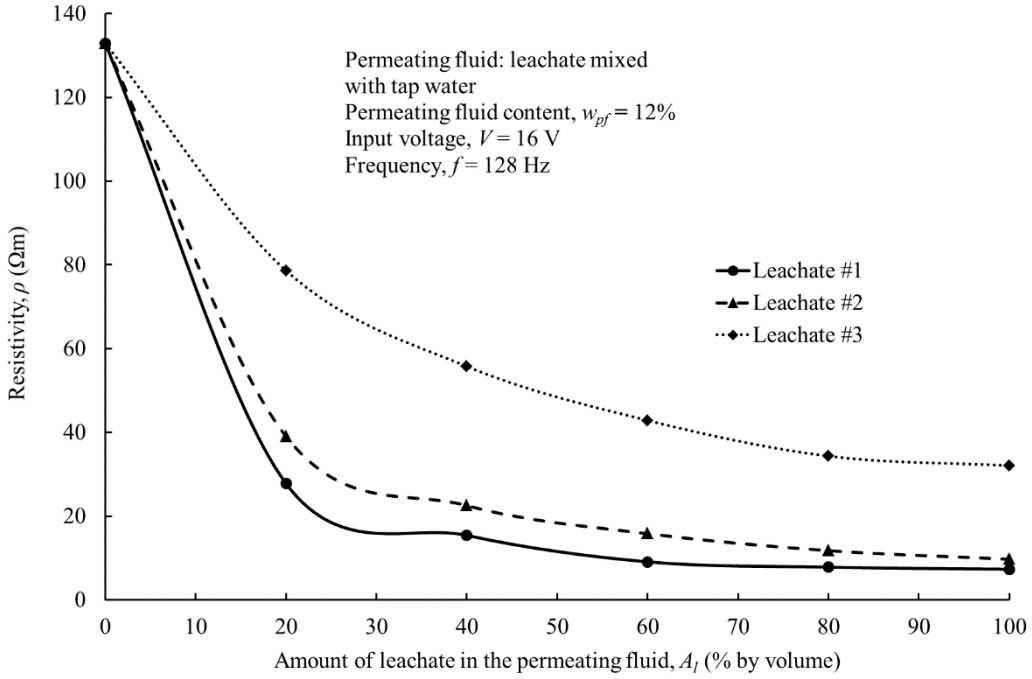

Fig. 5.9 Comparison of Leachate #1, Leachate #2 and Leachate #3 at permeating fluid content of 12%

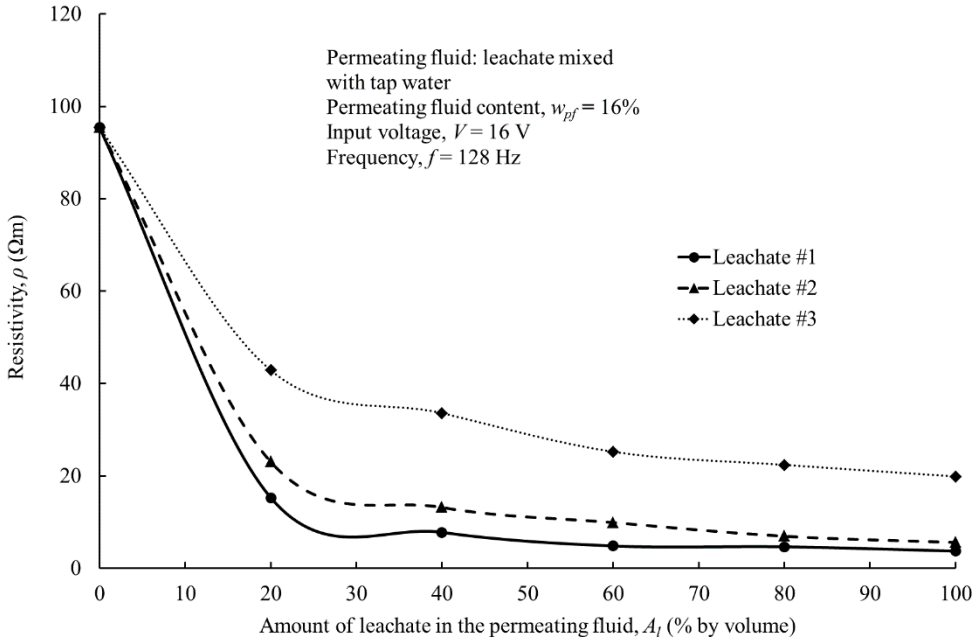

Fig. 5.10 Comparison of Leachate #1, Leachate #2 and Leachate #3 at permeating fluid content of 16%

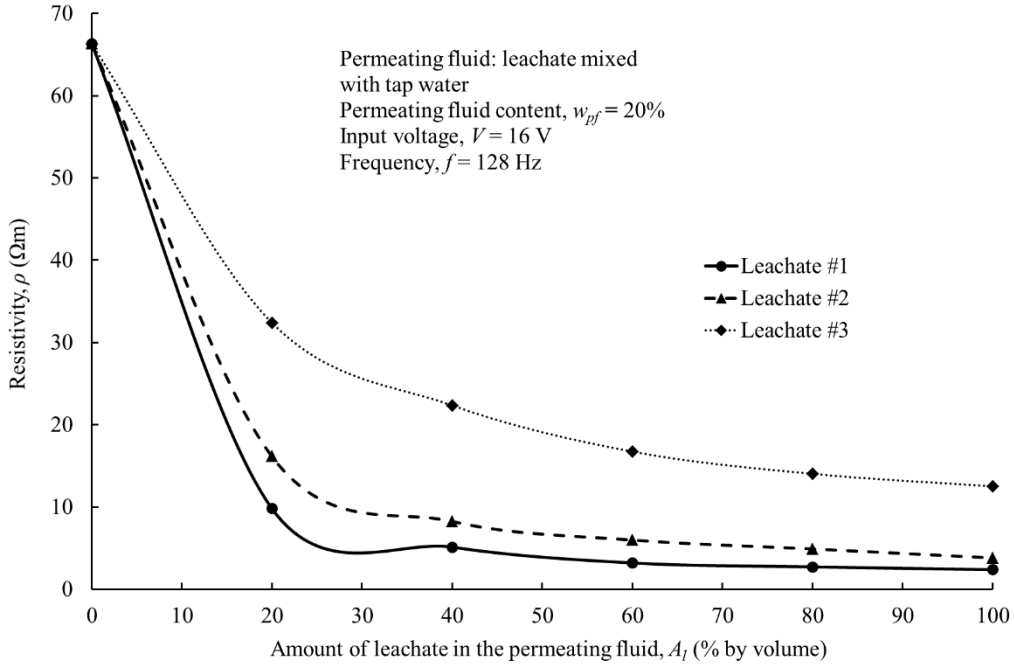

Fig. 5.11 Comparison of Leachate #1, Leachate #2 and Leachate #3 at permeating fluid content of 20%

It was noted that although the compositions of the three leachates are quite varied (Tables 3.3 through 3.5); Leachates #1 and #2 produce similar graphs. It can also be observed that the resistivity values are higher for Leachate #3 compared to the other two leachates.

For fluid contents greater than 12%, it can be noted from the figures that the disparity between the resistivity values of Leachate #1, #2 and #3 is considerably reduced. Additionally, with increasing A_l this disparity was found to show a decrease. However, the reduction in resistivity with increase in w_{pf} is more pronounced compared to the reduction observed due to an increase in A_l. Consequently, it can be inferred that the effect of the pore fluid content is more significant compared to the effect of amount or type of leachate for the Leachates #1, #2 and #3.

5.6 Development of correlations

From Figs. 5.1 through 5.3, it can be observed that the resistivity $\rho\,(\Omega\text{m})$ is inversely proportional to the permeating fluid content w_{pf} (%). Their relationship follows the trend given by the following equation:

$$\rho \propto \frac{1}{w_{pf}} \tag{5.1}$$

Using regression analysis for results obtained in Chapter 5 and from the equation 4.3, the variation of resistivity ρ of the sandy soil can be represented by:

$$\rho = c_1 C_o \left(c_2 - \frac{D_r}{100} \right) \left[\left(w_{pf} \right)^{-\left(\frac{100 c_3 C_o}{A_l} \right)} \right] \tag{5.2}$$

where

A_l (%) is the amount of leachate in the permeating fluid

$c_1\,(\Omega\text{m})$, c_2(dimensionless) and c_3(dimensionless) are specific constants corresponding to a

particular soil type and permeating fluid

C_o (dimensionless) is a variable dependent on the composition of the permeating fluid

D_r (%) is the relative density and

w_{pf} (%) is the permeating fluid / pore fluid/ fluid content.

Here C_o is found to increase with an increase in amount of leachate A_l.

5.7 Conclusions

The variations in electrical resistivity of Perth sandy soil was scrutinized by using different types and amount of leachates. It was observed that the addition of even a small amount of leachate in the permeating fluid resulted in a considerable decrease in the resistivity. The resistivity exhibited a rapid decrease with increasing permeating fluid content. However, the rate of decrease reduced significantly for fluid contents over 9%, irrespective of the leachate type and amount. For the three leachate specimens, increasing the amount of leachate in the pore fluid resulted in a decrease in the resistivity. The rate of decrease in resistivity was found to be more significant for less than 20% leachate in the permeating fluid, irrespective of the leachate used. At a leachate content of 30% in the permeating fluid, curves for the Leachates #1, #2 and #3 demonstrated a point of inflection. The effect of changing the fluid content on electrical resistivity was found to be more significant than the effect of varying the amount or type of leachate for the leachates used in this study.

CHAPTER 6

ELECTRICAL RESISTIVITY OF SOIL WITH SEAWATER

6.1 General

This chapter investigates how seawater and seawater-leachate intrusion affects the electrical resistivity characteristics of landfill foundation soil.

6.2 Background

At times, a landfilling facility might be situating in close proximity to salt water bodies and for such landfill systems appropriate legislations and legislative authorities painstakingly strive to prevent any possible contamination issues. In Australia, the Department of Environment takes stringent to regulate the transportation and disposal of wastes to landfills. Additionally, the Waterways Conservation Act, 1976 was enacted to deal with the discharge or deposition of waste which might enter the waterways and cause damage through pollution to the water or water sources. It also provides a system of licences for the discharge or deposit of material in water or on land. The Western Australian Marine (Sea Dumping) Act, 1981 prohibits the dumping or incineration at sea of radioactive material, wastes and other material without a permit in Western Australian waters.

However, as landfill liners operate under extreme physicochemical environments, there is a possibility of liner failure and subsequent contamination hazard. Timely detection and control of contamination is essential for pollution prevention. In any electrical resistivity contamination detection, it is necessary to understand how seawater, seawater-leachate intrusion affects resistivity. These tests were designed keeping in mind these requirements and contingencies.

This section takes to consideration the possibility of a leakage in a landfilling facility located near seawater. This chapter presents the results from experimentation conducted to investigate the effect of landfill leachate on the electrical resistivity of Perth sandy soil

infiltrated with seawater. Seawater collected from Coogee beach, Perth, Western Australia (WA) was used for the study. Experiments have been conducted by varying the seawater content from 0% to 100% to study its effect on the electrical resistivity of Perth soil. Tap water was used as a representation of groundwater. Leachate #1 obtained from Tamala Park landfilling facility, WA was used to observe the electrical resistivity variations produced by using different proportions of landfill leachate, seawater and tap water. The relative density was kept fixed at 50%. An AC-input voltage of 16 V and AC-input frequency of 128 Hz was used. The water content has been replaced by permeating fluid/ pore fluid/ fluid content in this chapter as various seawater-tap water-leachate mixes have been used to prepare the soil specimens for experimentation.

6.3 Effect of seawater

Figs. 6.1 and 6.2 denote the results obtained when seawater-tap water mixture is used as pore fluid. Figure 6.1 shows how the resistivity varies with change in the fluid content w_{pf}. The variation of resistivity with the amount of seawater in permeating fluid A_s is depicted in Figure 6.2.

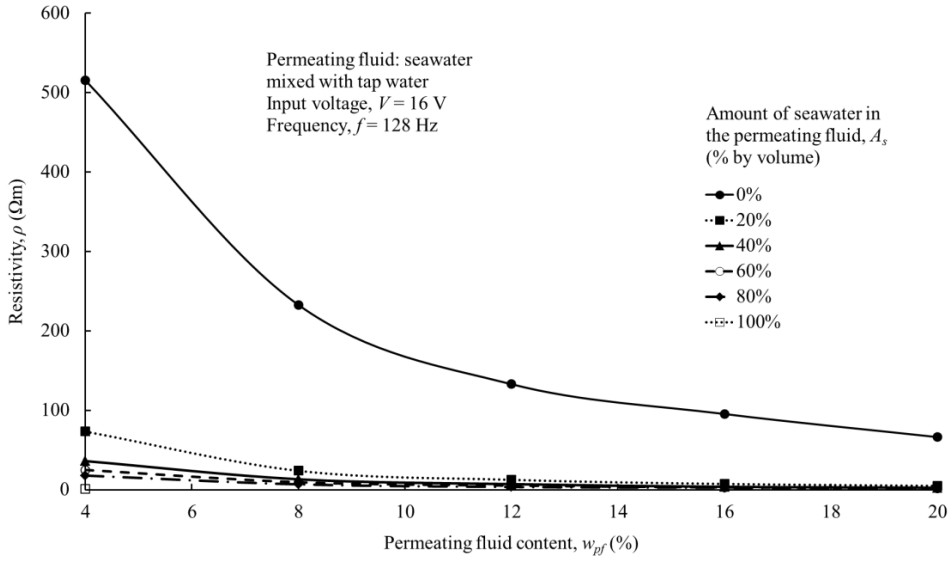

Fig. 6.1 Variation of resistivity with permeating fluid content with seawater-tap water mixture as permeating fluid

The resistivity ρ was found to show a rapid decrease with increase in the permeating fluid content till w_{pf} reaches 9%. After 9%, the rate of decrease of resistivity is reduced considerably with increase in w_{pf} .

It is apparent (Figs. 6.1 and 6.2) that for any fluid content w_{pf} the resistivity shows a sharp fall with increase in A_s . For w_{pf} = 4%, ρ = 515.533 Ωm when A_s = 0%, while ρ = 73.250 Ωm for A_s = 20%.

However, this observed disparity in resistivity with increase in the amount of leachate A_s is more significant for A_s less than 20%. Furthermore for A_s from 0% to 20%, the drop in resistivity decreases with increasing w_{pf} . Hence, it may be inferred that for A_s greater than 20% and w_{pf} = 9%, the resistivity is nearly constant.

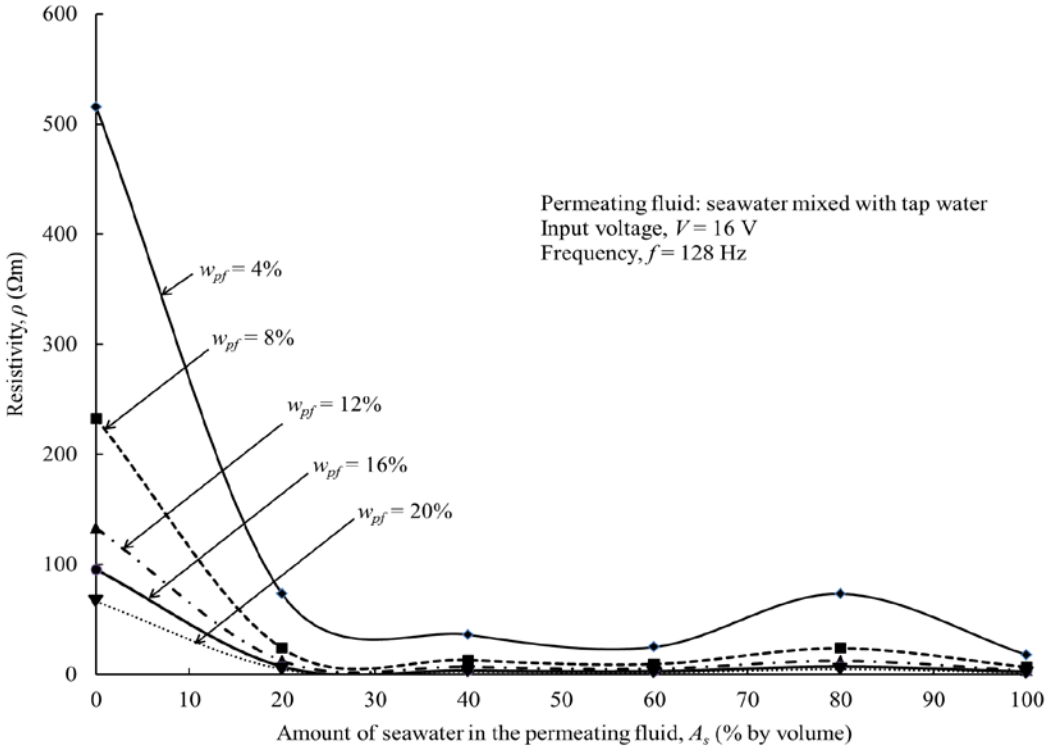

Fig. 6.2 Variation of resistivity with the amount of seawater in the permeating fluid (% by volume)

It can also be noticed from Figure 6.2 that resistivity value exhibits a maximum at A_s = 80%, irrespective of the pore fluid content. For any w_{pf}, the resistivity decreases rapidly with increase in A_s. This rate of decrease is reduced significantly after A_s = 25%.

6.4 Effect of Leachate #1 mixed with seawater

Figures 6.3 and 6.4 pertain to results obtained by using a mixture of Leachate #1 and seawater as permeating fluid. The variation of resistivity with permeating fluid content w_{pf} is shown in Fig. 6.3. Fig. 6.4 gives the variation of resistivity with increase in the amount of leachate added to the pore fluid A_l.

The resistivity decreases rapidly with increase in the fluid content for w_{pf} less than 9%. For w_{pf} greater than 9%, the change in resistivity becomes more gradual. For w_{pf} more than 14%, the resistivity is nearly constant.

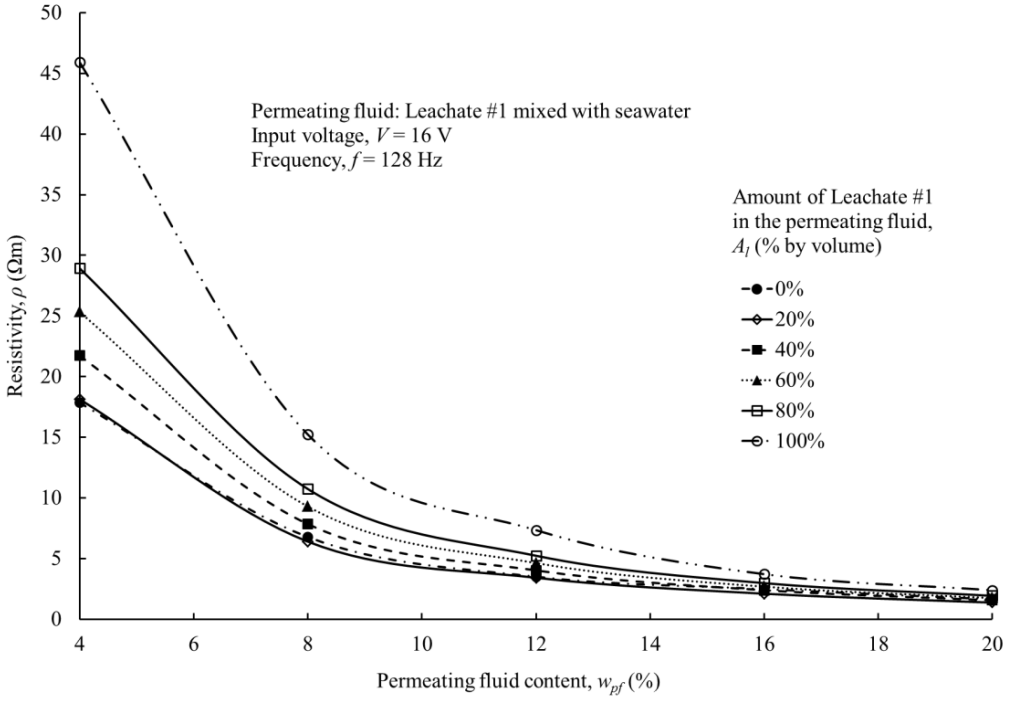

Fig. 6.3 Variation of resistivity with permeating fluid content with Leachate #1-seawater mixture as permeating fluid

It can be noted from Figs. 6.3 and 6.4 that an increase in the amount of leachate in the permeating fluid results in an increase in the resistivity. This increase is more apparent at lower permeating fluid content. At w_{pf} greater than 12%, the resistivity becomes fairly steady with increase in amount of leachate A_l. Mixing leachate in seawater would cause precipitation of various salts, thereby resulting in reduction of free ions for charge transfer. This might be the possible cause for the resistivity reduction with increase in A_l, as observed in Figs. 6.3 and 6.4.

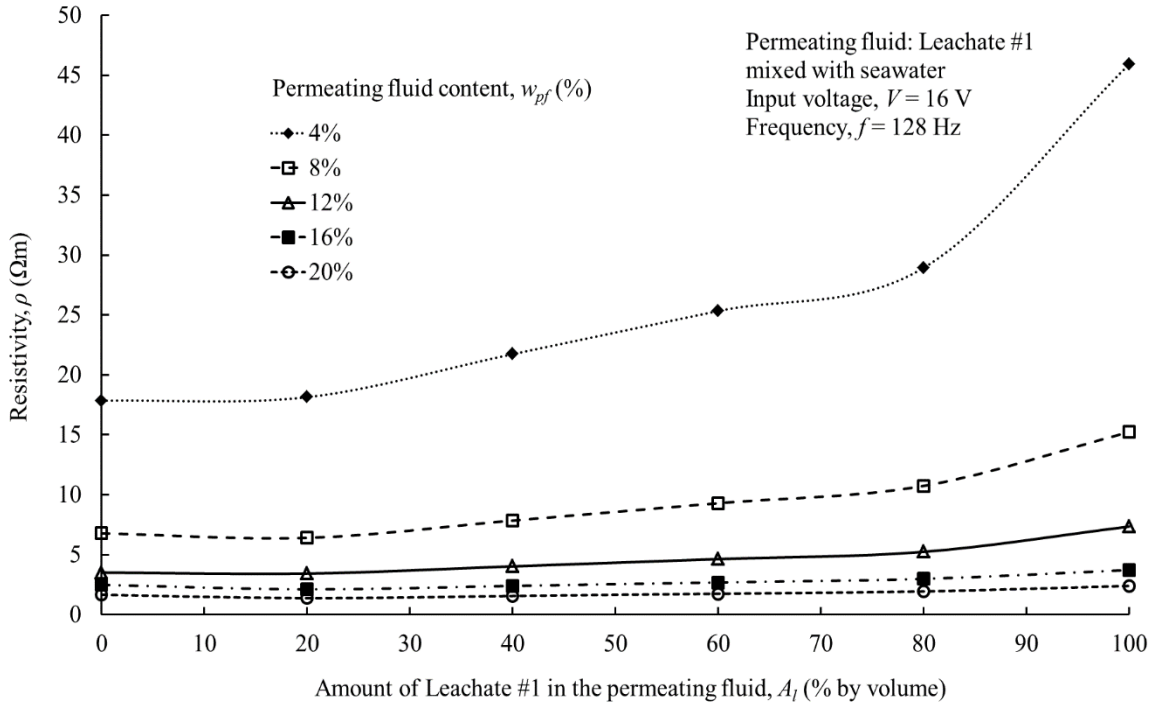

Fig. 6.4 Variation of resistivity with the amount of Leachate #1 in the permeating fluid (% by volume)

6.5 Effect of Leachate #1-seawater-tap water mixture

Figure 6.5 depicts the variation of resistivity with permeating fluid content using leachate-seawater-tap water mixture. Equal amounts of Leachate #1, seawater and tap water were used to make the permeating/pore fluid.

The resistivity was found to show a steady decrease with increase in the permeating fluid content w_{pf} . However, for w_{pf} from 8 to 12% the resistivity is observed to be nearly constant. The rate of decrease of resistivity with increase in w_{pf} for fluid content less than 8% is sharper than the rate of decrease observed for w_{pf} greater than 12%.

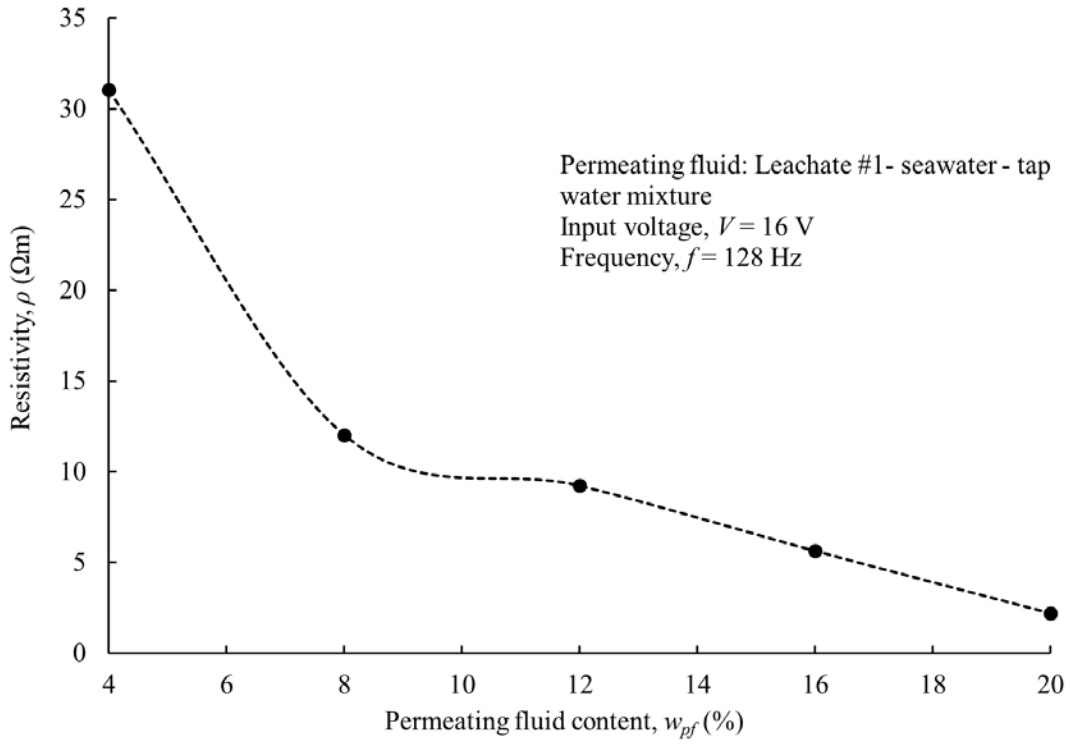

Fig. 6.5 Variation of resistivity with permeating fluid content using Leachate #1-seawater-tap water mixture

6.6 Comparison of Leachate #1 mixed with seawater and with tap water

Leachate #1 was mixed with tap water and then with seawater and used as pore fluids for sandy soil mixtures. Figs. 6.6 through 6.10 show how the changes in the type of fluid used cause variation in resistivity. Fig. 6.6 gives the variation in resistivity with increase in amount of leachate in permeating fluid A_l at a fluid content w_{pf} of 4%. Figs. 6.7 through 6.10 depict

similar results for w_{pf} of 8% to 20%.

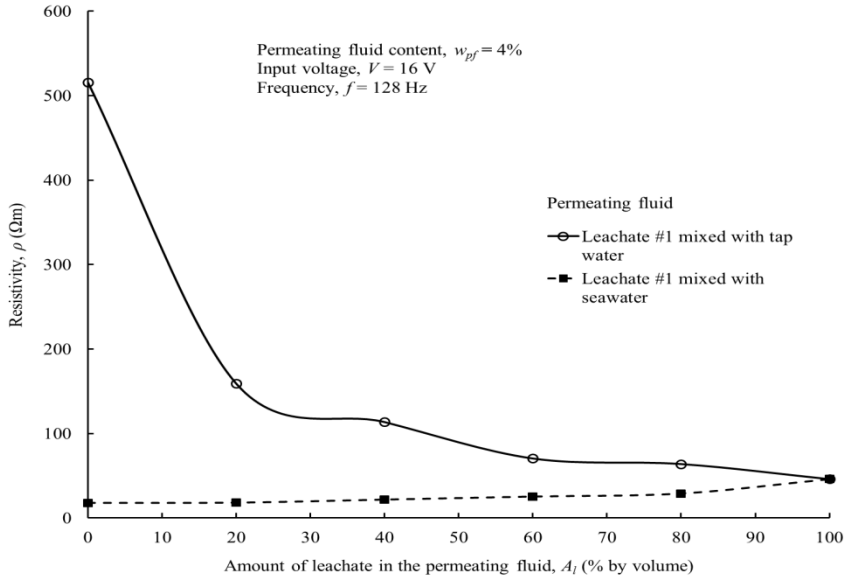

Fig. 6.6 Comparison of leachate-seawater mixture and leachate-tap water mixture at permeating fluid content of 4%

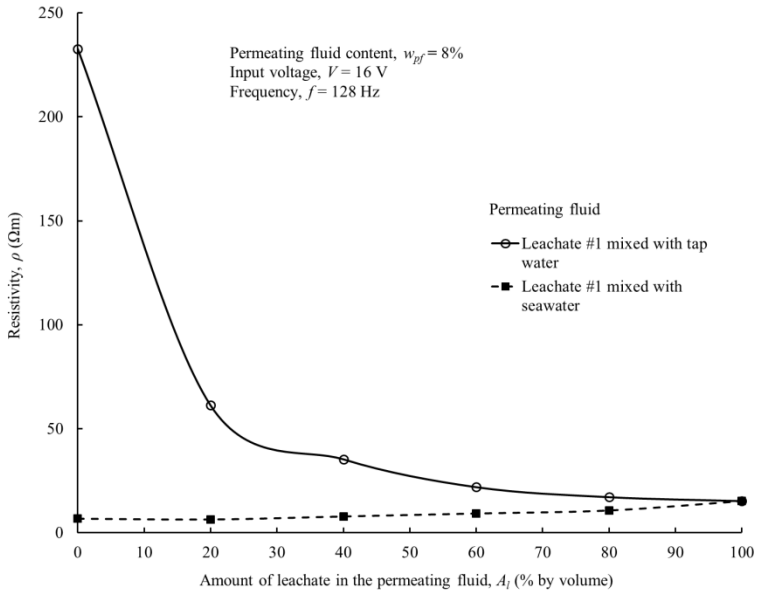

Fig. 6.7 Comparison of leachate-seawater mixture and leachate-tap water mixture at permeating fluid content of 8%

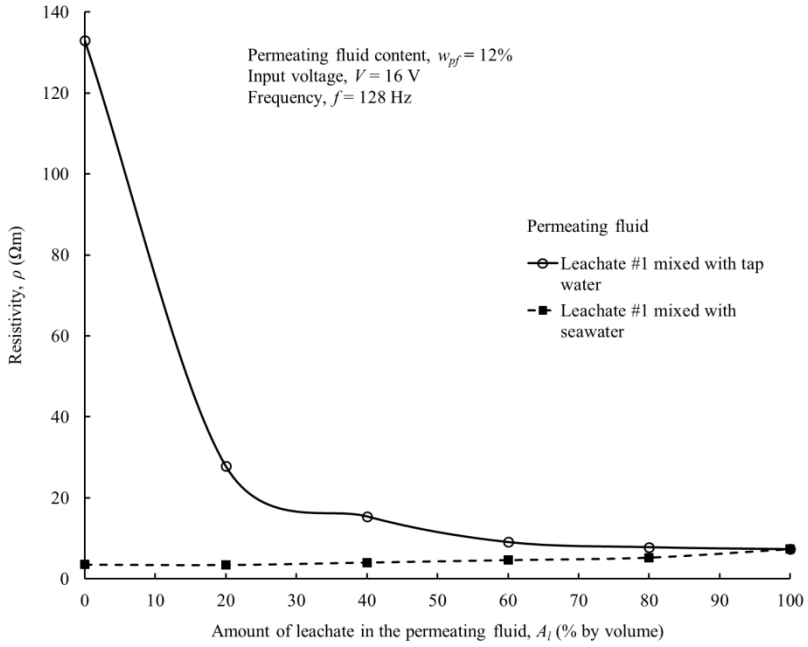

Fig. 6.8 Comparison of leachate-seawater mixture and leachate-tap water mixture at permeating fluid content of 12%

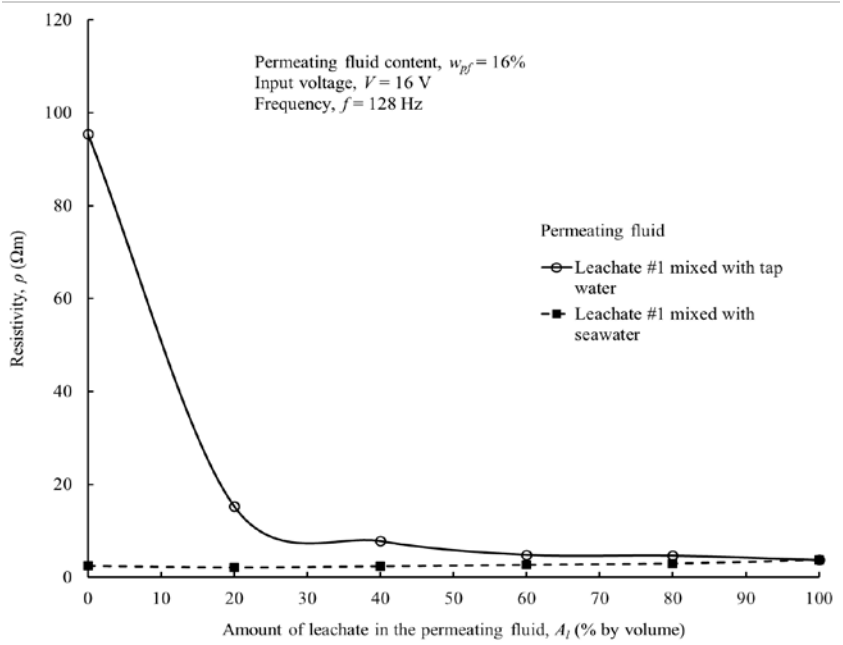

Fig. 6.9 Comparison of leachate-seawater mixture and leachate-tap water mixture at permeating fluid content of 16%

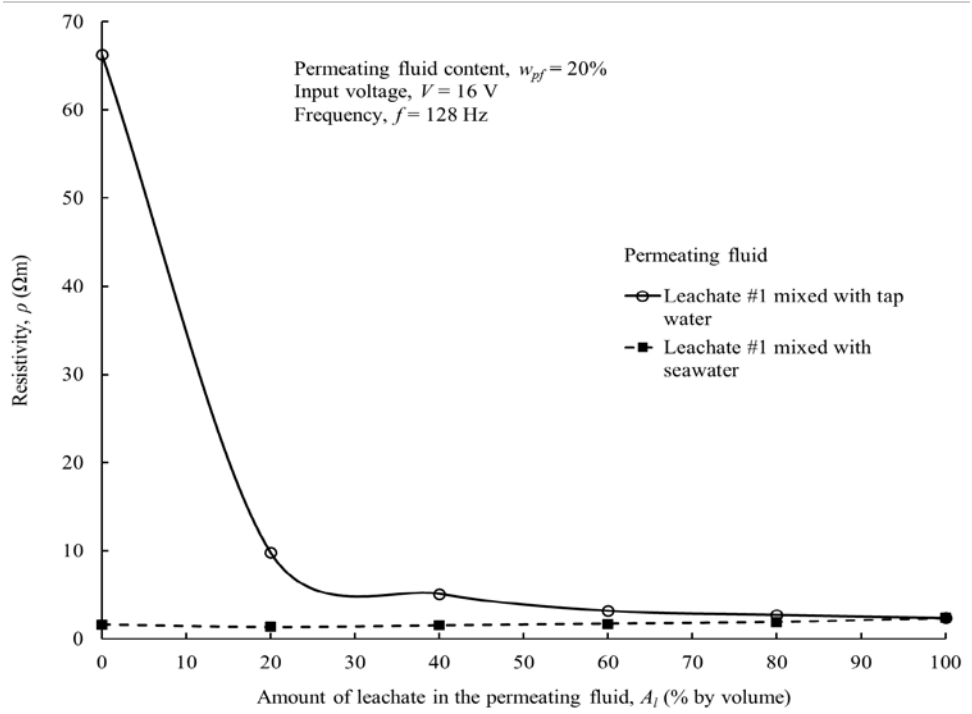

Fig. 6.10 Comparison of leachate-seawater mixture and leachate-tap water mixture at permeating fluid content of 20%

It can be observed that the Figs. 6.6 through 6.10 exhibit similar graphs. However, the value of resistivity decreases with increase in the permeating fluid content for leachate-tap water mix. It is interesting to note that the resistivity is nearly constant for leachate-sea water mixture, irrespective of the amount of leachate and the fluid content. Slight increase in resistivity is observed at low w_{pf} and high A_l, but this change is fairly insignificant.

Furthermore with increase in w_{pf}, the disparity in resistivities of leachate-seawater mixture and leachate-tap water mixture was found to reduce considerably, irrespective of A_l. This decrease in disparity was noted to be more significant with increase in the amount of leachate in the pore fluid, irrespective of fluid content.

6.7 Development of correlations

For seawater-tap water mixture used as pore fluid, the graph is observed to be very similar to the

graphs obtained in Chapter 5 for the leachate-tap water mixtures. It should be noted that tap water has lesser ions (Table 3.2) and consequently lower conductivity than the three leachates (Tables 3.3, 3.4 and 3.5) and seawater (Fig. 3.7) used for this research work. Hence, addition of even a small amount of leachate or seawater to tap water produces a decrease in resistivity compared to the resistivity obtained when only tap water is used as permeating fluid.

Leachate #1-tap water mixture was found to exhibit much higher resistivity compared to seawater-tap water mixture. Therefore, it can be inferred that the seawater has more ions than Leachate #3. Hence, with increase in the amount of leachate added to seawater, the resultant resistivity shows an increase. Furthermore, there is a possibility of reaction and resulting precipitation of salts occurring in the leachate-sea water mixture which would also account for the observed decrease in resistivity.

Taking these results and observations into consideration the following equations are proposed for resistivity $\rho\,(\Omega\mathrm{m})$:

$$\rho = c_1 C_o \left(c_2 - \frac{D_r}{100} \right) \left[\left(w_{pf} \right)^{-\left(\frac{100 c_3 C_s}{As} \right)} \right] \tag{6.1}$$

for soil infiltrated with seawater and

$$\rho = c_1 C_o \left(c_2 - \frac{D_r}{100} \right) \left[\left(w_{pf} \right)^{-\left(\frac{100 c_3 C_{sl}}{A_l} \right)} \right] \tag{6.2}$$

for soil infiltrated with seawater-leachate mixture,

where

A_l (%) is the amount of leachate in the permeating fluid

A_s (%) is the amount of leachate in the permeating fluid

$c_1\,(\Omega\mathrm{m})$, c_2(dimensionless) and c_3(dimensionless) are specific constants corresponding to a particular soil type and permeating fluid

C_s(dimensionless) is a variable dependent on the composition of the seawater

C_{sl} (dimensionless) is a variable dependent on the composition of the seawater-leachate mixture

D_r (%) is the relative density and

w_{pf} (%) is the permeating fluid/ pore fluid/ fluid content.

Here C_s is found to increase with an increase in the amount of seawater in the seawater-tap water mixture A_s and C_{sl} decreases with an increase in the amount of leachate added to seawater A_l.

6.8 Conclusions

The resistivity of soil permeated with seawater-tap water mix registers a sharp decrease with increase in the permeating/ pore fluid content. However, the rate of decrease of resistivity is reduced considerably for fluid content greater than 9%. The resistivity exhibits a local maximum when the amount of seawater in the permeating fluid content is 80%, irrespective of the fluid content. For any pore fluid content, the resistivity decreases rapidly with increase in the amount of seawater. This rate of decrease is reduced significantly after 25%. Similar result is observed for the leachate-seawater mixture. The resistivity decreases rapidly with increase in the permeating fluid content less than 9%. However, for pore fluid content greater than 9%, the change in resistivity is gradual and nearly constant after 14%. Furthermore, an increase in the amount of leachate in the pore fluid results in an increase in the resistivity. This increase is more apparent at lower permeating fluid content. At fluid contents greater than 12%, the resistivity becomes fairly steady with increase in the amount of leachate. For Leachate #1-seawater-tap water mixed in equal proportions, the resistivity was found to show a steady decrease with increase in the permeating fluid content. The resistivity is steady for fluid contents between 8% to 12%. A sharper rate of decrease is noted for pore fluid content below 8% than for more than 12%. Comparison of results obtained for leachate-seawater mixture with leachate-tap water mixture yields that the value of resistivity decreases with increase in the fluid content for leachate mixed with tap water. However, the resistivity is nearly constant for leachate-sea water mixture, irrespective of the amount of leachate and the permeating fluid content. The disparity in

resistivities of leachate-seawater mixture and leachate-tap water mixture was found to reduce considerably, irrespective of the amount of leachate. This decrease in disparity was noted to be more significant with increase in the amount of leachate in the pore fluid, irrespective of the fluid content.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

Liners are used extensively for contaminant control and pollution prevention. However, liner integrity over intended design life cannot be ascertained (Rowe *et al.*, 2004) as they operate under extreme physicochemical conditions. Leakages occur frequently with ensuing pollution of soil and groundwater. Timely detection of contamination is imperative for pollution control (Harrop-Williams, 1985). Geophysical techniques such as the electrical resistivity method can assist in expeditious, non-invasive control of contamination at low costs.

The electrical resistivity method is based on the well-established fact that the electrical resistivity of soils is much higher than the electrical resistivity of water, leachates or any liquid effluents (Abu-Hassanein *et al.*, 1996; Shukla & Yin, 2006). Hence, infiltration of even a small of amount of any of these permeates causes an alteration in the electrical properties of geomaterials which can easily be detected by the use of the electrical resistivity method (Darayan *et al.*, 1998; Yoon & Park, 2001).

Furthermore, the electrical and geotechnical properties of geomaterials are closely related. By varying one, the other can be altered. The knowledge of the relationship between geotechnical and electrical properties of soils has many other useful applications in civil as well as environmental engineering such as predicting the value of one from the other (Kalinski & Kelly, 1993), contamination detection, corrosion studies (BSI, 1990a), anomaly detection (Panthulu *et al.*, 2001), soil salinity studies (Adam *et al.*, 2012; Gupta & Hanks, 1972; Rhoades *et al.*, 1977), agricultural applications (Samouelian *et al.*, 2005). Therefore, many researchers have forayed into investigating this relationship (Archie, 1942; Fukue *et al.*, 1999; Gupta & Hanks, 1972; Kalinski & Kelly, 1993; Kibria & Hossain, 2014; Kuranchie *et al.*, 2014; McCarter, 1984; McCarter & Desmazes, 1997; Munoz-Castelblanco *et al.*, 2012; Sreedeep *et al.*, 2004; Yan *et al.*, 2012; Yoon & Park, 2001). Although, some of these previous research works

have made significant contribution, yet there is a lack of experimental results specifically applicable to the correlation of electrical resistivity of Perth sandy soils with geotechnical parameters such as water content and relative density. Different standards (ASTM, 2011a, 2011b, 2012b, 2015a, 2015b, 2015c; BIS, 1987; BSI, 1990a, 1990b; Standards Australia, 1997) have subscribed methods for the testing of electrical resistivity of soils and leak detection in liners, but these standards are not very clear on either the type of metal electrode to be used or the ranges of input voltage and frequency. Hence, there is a need for more specific details in this regard, taking into consideration both water content and relative density.

Additionally, many previous research works have focused on the use of the changes in electrical properties of soil for the detection of contamination (Darayan *et al.*, 1998; Yoon & Park, 2001) but not much work has been done to observe the changes in resistivity produced by gradually increasing the amount of contaminant. Such a study would produce results which can find application in the development of sensors for landfill leakage detection and location.

For landfilling facilities situated in close proximity to salt water bodies like seas and oceans, infiltration of landfill base materials with seawater and seawater- leachate mixture would produce variations in electrical resistivity. Investigation of the electrical resistivity behavior in such cases could assist in the detection and control of contamination in such systems.

Consequently, keeping in mind the aforementioned, experiments were conducted to investigate the relationship of electrical resistivity of sandy soil with water content and relative density, focusing specifically on the effects of AC-input voltage and AC-input frequency, electrode material and type of water on electrical resistivity measurements. Perth sandy soil, classified as poorly graded sand (SP), was used for experimentation. The electrical resistivity of several mixes of the soil was determined by conducting tests in accordance with AS 1289.4.4.1-1997 (Standards Australia, 1997).

The effect of leachates on electrical resistivity of soil was investigated by using three types of leachates. The leachates were added to tap water in various proportions to make pore fluids. Seawater-tap water mixtures and seawater-leachate mixtures were also used as permeating fluids to investigate the effect of infiltration of seawater and seawater-leachate on landfill foundation materials.

Based on the results of the study, the electrical resistivity method was found to be an efficient and suitable method for contamination detection and quantification. Several correlations were also developed from the obtained results and observations.

7.2 Conclusions

Based on the results of this study, the following conclusions are made:

- The electrical resistivity of Perth sandy soil is independent of the AC-input voltage and frequency within the ranges used in this study.
- The resistivity of the sandy soil decreases rapidly with an increase in water content, but the rate of decrease reduces considerably for water contents over 12% in the case of distilled water and 10% for tap water, irrespective of the relative density. The resistivity shows an almost linear decrease with a corresponding increase in the relative density.
- The effect of varying the relative density on the electrical resistivity diminishes progressively with an increase in the water content.
- The type of permeating fluid used has a significant effect on resistivity whereas the electrode material has a negligible impact on the electrical resistivity measurements for the given test duration.
- For sandy soils permeated with water, the relative density and the water content/ fluid content can be used to predict electrical resistivity and vice versa.
- The addition of even a small amount of leachate in the permeating/ pore fluid results in a considerable decrease in the resistivity. The resistivity exhibits a rapid decrease with increasing fluid content. However, the rate of decrease reduces significantly for permeating fluid contents over 9%, irrespective of the leachate type and amount. For the three leachate specimens, increasing the amount of leachate in the pore fluid results in a decrease in resistivity. The rate of decrease in resistivity is more significant for less than 20% leachate in the fluid, irrespective of the leachate used.
- At a leachate content of 30% in the permeating fluid, curves for the Leachates #1, #2 and #3 demonstrate a point of inflection. The effect of changing the fluid content on electrical resistivity is more significant than the effect of varying the amount or type of leachate.

- The resistivity of soil permeated with seawater-tap water mix registers a sharp decrease with increase in the permeating fluid content. However, the rate of decrease of resistivity reduces considerably for fluid contents greater than 9%. This trend is similar to the case when leachate- tap water mix is used as permeant. Hence, in cases where landfills are situated close to seawater, an observed drop in electrical resistivity might be a result of seawater intrusion and not because of liner leakages.
- The resistivity exhibits a maximum when the amount of seawater in permeating fluid content is 80%, irrespective of the fluid content. For any pore fluid content, the resistivity decreases rapidly with increase in the amount of seawater. This rate of decrease reduces significantly after 25%.
- For the leachate-seawater mixture the resistivity decreases rapidly with increase in the permeating fluid content less than 9%. However, for fluid contents greater than 9%, the change in resistivity is gradual and nearly constant after 14%. Furthermore, an increase in the amount of leachate in the pore fluid results in an increase in the resistivity. This increase is more apparent at lower permeating fluid contents. At fluid contents greater than 12%, the resistivity becomes fairly steady with increase in the amount of leachate.
- For Leachate #1-seawater-tap water mixed in equal proportions, the resistivity exhibits a steady decrease with increase in the permeating fluid content. The resistivity is steady for fluid contents between 8% to 12%. A sharper rate of decrease is noted for pore fluid contents below 8% compared to fluid contents greater than 12%.
- The value of resistivity decreases with increase in the permeating fluid content for leachate mixed with tap water. However, the resistivity is nearly constant for leachate-sea water mixture, irrespective of the amount of leachate and the fluid content.
- The disparity in resistivities of leachate-seawater mixture and leachate-tap water mixture reduces considerably, irrespective of the amount of leachate. This decrease in disparity is more significant with increase in the amount of leachate in the pore fluid, irrespective of the permeating fluid content.
- Correlations between the electrical resistivity, the water content, the relative density, the amount and the composition of the pore fluid, which are applicable to the soil and permeating fluids used in the study, have also been developed.

It is important to note that the findings reported in this thesis should not be extrapolated to soils significantly different from the sandy soil used in this study. Furthermore, the experimental simplifications should be kept in mind while using the results reported here.

7.3 Recommendations for future work

Based on the findings of this research, it can be concluded that the electrical resistivity method is a viable option for the detection and quantification of various permeating/pore fluids infiltrating sand and other landfill foundation geomaterials. These results and the developed correlations reported in this thesis will have several positive applications in civil and environmental engineering projects. Further investigation of the following aspects is recommended, taking to account the research work and its limitations:

- Experimentation with more types of soil specimen.
- Study of sand amended with different bentonite contents.
- Using lesser increments for water content and permeating/pore fluid content, for example an increment of 2%.
- Conducting the tests with multiple number of leachates.
- Increments in the amount of leachates added to the permeating fluid to be kept lower, for example 10%.

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